Faculdade de Engenharia da Universidade do Porto

Smart Hydraulics Controller

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Resumo

Um problema atual dos sistemas de aquecimento instantâneo de águas sanitárias, por esquentador, é a dificuldade de se obter uma temperatura estável à saída do equipamento.

Entende-se por temperatura estável conseguir que ao longo do tempo a temperatura não varie substancialmente e que também, nos momentos de iniciação e pós interrupção, não haja variações de temperatura abruptos que possam ser bastante incómodos e até mesmo prejudiciais para o utilizador.

Deste modo, foram estudados os vários conceitos físicos presentes no sistema para assim se compreender melhor quais os possíveis métodos para controlar o esquentador, por modo a conseguir suprimir temperaturas indesejadas e assim aumentar o conforto do utilizador.

No presente documento, são demonstrados os procedimentos realizados no desenvolvimento de soluções possíveis, por modo a se conseguir atingir o objetivo principal.

Foi realizado um modelo geral de um aparelho em plataforma Matlab/Simulink e, através do mesmo, em simulação computacional, projetaram-se várias possibilidades de controlar o sistema.

No final deste documento são apresentados resultados experimentais relativamente ao método de variação de parâmetros de PID e resultados simulados quanto ao método de *Bypass*.

Abstract

One of the actual problems regarding to instantaneous water systems, in particular gas water heaters, is the difficulty to obtain a stable temperature in the output of the heater.

It is understood by stable, a heater capable of providing a response over time without substantial variations in temperature and, in the start and after a brief interruption, there are no abrupt overshoots and undershoots which can be very uncomfortable and also harmful to the user.

Thus, in this document are studied with some detail the physics involved and reviewed a few possible methods for the control architecture of the gas water heaters in order to suppress unwanted temperatures and this way, improve the comfort to the user.

In this thesis are demonstrated the procedures made in the development of a possible solution which can achieve the main goal with respect to the European standard EN13203.

A model of the whole system was implemented in computational environment, Matlab/Simulink. This way, was possible to develop and test different control methodologies.

At the end of this document are presented the experimental results from the PID Gain Scheduling and model implementation of the bypass control.

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Contents

List of Figures

List of Tables

Abbreviations and Symbols

Abbreviations (alphabetical order)

AFR	Air-Fuel Ratio
AG	*Aktiengesellschaft*
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
DEEC	Departamento de Engenharia Eletrotécnica e de Computadores
DFT	Discrete Fourier Transform
ECU	Electronic Control Unit
EU	European Union
EN	European Standard
ETSI	European Telecommunications Standards Institute
FEUP	Faculdade de Engenharia da Universidade do Porto
GmbH	*Gesellschaft mit beschränkter Haftung* (Company with limited liability)
HHV	Higher Heating Value
HMI	Human Machine Interface
I&D	Innovation and Development
LFL	Lower Flammable Limit
LHV	Lower Heating Value
MIMO	Multivariable Input and Multivariable Output
MPC	Model predictive control
MV	Manipulated variable
PID	Proportional Integrative Derivative
PT_1	First order lag element
PWM	Pulse with modulation
RPM	Revolutions per minute
SA	*Sociedade Anónima*
TS	Takagi-Sugeno
UFL	Upper Flammable Limit

Symbols

A	Area
C_{flow}	Fan law flow coefficient
$C_{pres.}$	Fan law pressure coefficient
C_{power}	Fan law power coefficient
C_p	Specific heat capacity at constant pressure
D	Bypass ratio
e	Control error
E_K	Kinetic Energy
E_P	Potential Energy
g	Gravitational acceleration
m	Mass
$\dot{m}$	Mass flow
M	Molar mass
n	Amount of substance
N	Fan speed
L	Length
P	Pressure
Q	Heat
$\dot{Q}$	Heat Power
R	Ideal gas constant
T	Temperature
T_i	Integral time
T_d	Derivative time
U	Internal Energy
V	Volume
$\dot{V}$	Volume Flow
W	Electric Power
h	Heat transfer coefficient
h_s	Sample time
k	Thermal conductivity
K_c	Controller gain
K_D	Derivative gain
K_I	Integrative gain
K_P	Proportional gain
λ	Air-Fuel Equivalence Ratio

ε	Surface emissivity
ρ	Mass density
σ	Stefan-Boltzmann constant

Chapter 1

Introduction

This dissertation is prepared to develop a smart hydraulics controller for a new generation of gas water heaters, providing a comfort optimization for the user. This will be done by means of controlling a set of actuators within the hydraulic system.

In this chapter is presented the specific objectives, motivation regarded by this new generation product and the structure of the whole document.

1.1. Motivation

The energy consumption is seen today in a more relevant way than a few decades ago therefore all new equipments have a common factor, energy efficiency allied with maximum comfort.

The gas water heater is one of the most used equipment in domestic dwellings for instantaneous water heating. The principle of operation of the heater is based on fuel fossil. It is not totally right to think that the water heater is a non-eco-friendly equipment compared to other heating systems, however, it should be kept in mind that it consumes directly fuel fossil, which in some cases can be used in a power plant for production of electrical energy that powers other water heating systems, thus lowering the overall efficiency of them.

It is therefore important to achieve the greatest possible comfort for the consumer, which will be the focus of this work, without compromising the efficiency.

The possibility to develop this work in Bosch Termotecnologia SA, is very attractive because it allows to work in a professional environment of innovation and research.

1.2. The Company

Bosch Group

On November 15, 1886, Robert Bosch (1868-1942) received official approval to open a “Workshop for precision Mechanics and Electrical Engineering” in Stuttgart. This how the company as we know it started, Robert Bosch GmbH (known only for Bosch).

On November 4, 1932, Robert Bosch AG acquired Junkers & Co. GmbH, which manufactured gas-fired heating and hot water systems in Dessau. The acquisition marked the beginning of today’s thermo technology division.

All over the years the company spread over the world, opening offices and manufacturing plants. Today, presents itself as one of the largest private industrial corporations in the world. As a result, Bosch Portugal is one of the subsidiaries of the group actuating in several areas as: automotive technology; industrial technology and consumer equipments technologies (as a part of it, Bosch Termotecnologia SA).

Bosch Termotecnologia SA

On March 17, 1977, Vulcano Termodomésticos SA started is activities, producing gas water heaters under a license agreement with Robert Bosch GmbH.

On 1983, the Bosch Group acquired Vulcano and two years later, in 1985, Vulcano established itself as Portuguese market leader in gas water heaters.

On 1992, Vulcano Termodomésticos SA reaches European leadership of gas water heaters.

Nowadays as Bosch Termotecnologia SA, the company produces not only gas water heaters but wall mounted boilers, solar heating and heat pumps. This is due to a R&D department in charge of the design and development of new products.

1.3. Objectives

The existence of temperature overshoots, undershoots and adverse transient responses in the hot water flow provided by instantaneous gas water heaters is presented as a major problem in providing a stable temperature for final consumer. This fact is due to the inertia presented in the whole system, constituted by the water heater itself and the water distribution system to the point of consumption.

In order to provide a solution to this problem the focus of this dissertation will be the development of a controller suitable for instantaneous gas water heaters that minimizes the variations of non-wanted temperatures.

In other words we can say the main objective is the improvement of the user comfort.

1.4. Document Structure

Here is presented how the document is divided and explained the content of each division, table 1.1 demonstrates those divisions. The subdivisions are not discussed here.

This first chapter seeks to introduce the main goal of the dissertation and all the parts involved.

Chapter 2 introduces and explores the technologies referred to the system in study.

Chapter 3 details the models and simulations made in order to provide a base for the control architecture.

Chapter 4 demonstrates and explains the control implemented and its results.

Chapter 5 presents the whole project work, final conclusions and suggestions for possible future developments.

Table 1.1 - Document Structure

Chapter	*Title*
1	Introduction
2	State of Art
3	System Modeling
4	Implementation and Results
5	Conclusions

Chapter 2

State of Art

This chapter introduces and explores the technologies referred to the system in study. For that, a theoretical background must be comprehended also with the understanding of the overall matters. The different matters are divided in this chapter by four stages.

The first section refers to the gas water heaters. An explanation about how it works and the processes related.

In the second section the thermodynamics and fluids of the gas water heaters are explored, this section is particularly important for understanding the dynamics that are presented in the system.

The third refers to the control method that will be considered for the application. In this case Fuzzy logic will be the base on the controller algorithm.

The fourth and last introduces some regulations regarded to the EU and some safety requirements.

2.1. Gas Water Heater

In the past there wasn't hot water for everyone, only the wealthy ones were capable to afford it. Hot water might be relevant for some people to bath regularly, as a consequence, there was an improve in hygiene. To surpass that problem, people start to heat water in many different ways. One of the most common ways was heating water to a storage tank but that was a time-consuming ordeal. Through ages the development of equipment with more comfort and efficiency was a need for society. With time and engineering work the instantaneous gas water heaters finally appeared.

The basic idea of a gas water heater is the energy transformation of a gas fuel fossil into heat to the water, considering this transfer of heat instantaneous.

2.1.1. Working principle

In a general way, gas water heaters have the same base of working principle. The model process can be described by the follow steps, considering for example the gas water heater in Fig. 2.1:

(i) A valve or water tap of hot water is opened;

(ii) Cold water starts flowing through the heater system and activates a flow sensor given the information to the ECU that is necessary to heat water;

(iii) This third step depends on the type of system, however in a simple manner, it's when there is combustion on the chamber;

(iv) The cold water flows through the tubes coupled to the combustion chamber and heats;

(v) If there is, a temperature sensor at the output of the tubes coupled to the combustion chamber informs the ECU the actual temperature;

(vi) The ECU adjusts the combustion in order to provide the reference temperature imposed by the user;

(vii) When the valve or water tap of hot water is close the water stops flowing through the system and again the water flow sensor give that information to the ECU and this stops instantaneously to gas flow.

This way is relevant to describe all the components presented in this whole control steps.

1 Exhaust
2 Heat exchanger
3 Burner
4 Blower
5 HMI
6 Flow sensor
7 Hot water Out
8 Gas supply
9 Cold water In
10 Cold water pipe

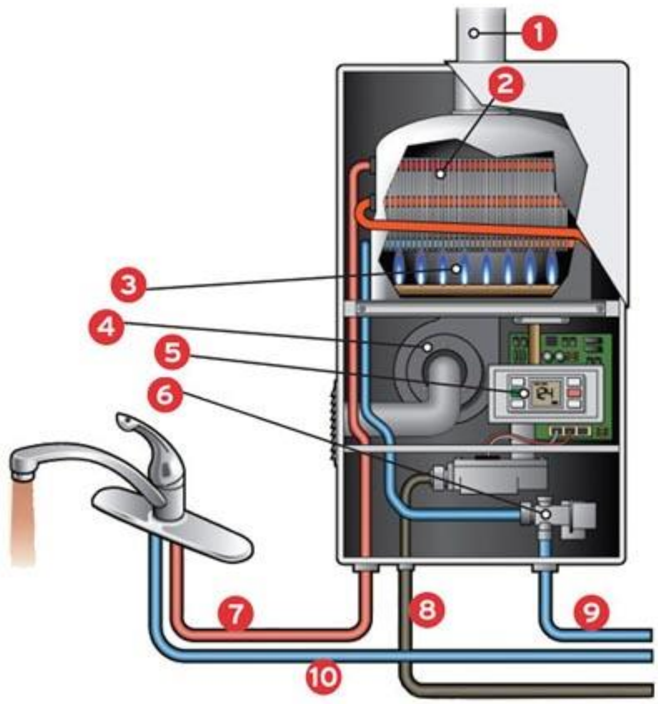

Figure 2.1 - Gas water heater physic configuration

(1) **Exhaust** - This component is responsible for the exhaust of gases resulting from the combustion. Some heaters have different architecture of exhaust in consequence of the chimney structure.

(2) **Heat Exchanger** - Being this the core of heater is there where the energy provided by the gas fuel transforms in heat to the water. This process depends on several aspects that will be taken into account for the control system processed in the ECU. The efficiency of the heater also depends on the capability of heat transfer of this part.

(3) **Burner** - It's in the burner where the gas fuel is expelled to the heat exchanger by a controlled way. Provides a stable and homogeneous flame.

(4) **Blower** - The blower is responsible for the inlet air to the combustion chamber. With the capability of controlling the RPM it's possible to control the air flux and static pressure that is provided.

(5) **HMI** - Human machine interface permits the user to easily configure the machine to its defined values of working, like hot water temperature in this case.

(6) **Flow Sensor** – Provides to the ECU water flow requested by the user, very important for the control, and also indicates when is necessary to start the heater. Also here, there is a possibility to have a controlled flux restrainer.

(7) **Hot water out** – The hot water output is the most important in the perspective of final control. Is there were the goal will be present, so in the hot water output, depending where we consider it is (in the output of the heat exchanger or elsewhere) its needed to have temperature sensors to give the right feedback to the ECU.

(8) **Gas supply** – It's from the gas supply that the heater gets its energy in the shape of fuel gas fossil, usually natural gas, propane or butane.

(9) **Cold water in** – This is the fundamental resource of working, without it would be useless. It's also important for control that the cold water temperature is acquired by temperature sensors.

(10) **Cold water pipe** – Not relevant if the user sets the right temperature in the HMI but relevant if the user wants a lower temperature.

2.2. Thermodynamics and Fluids

To comprehend the energy process in the gas water heater is important to have a general study base in thermodynamics and fluids. As being a gas heater its source of energy is fuel, so there will be combustion. This way is relevant to understand well the principal components that will affect the combustion in a way that will be possible to control them by the ECU to get the right heat from the combustion. With this process is possible to transfer the energy to water and then accomplish the ultimate goal, a stable and precise hot water temperature.

2.2.1. Thermodynamics

J. P. Joule carried out some precise experiments on the nature of heat and work. The results of his experiments are very important for understanding the first law of thermodynamics and the concept of energy. He found out that an amount of work per unit mass, done in an insulated recipe with water by a stirrer, raised the temperature of the water. Then the initial temperature could be restored by the transfer of heat through a contact with a cooler object. Thus Joule was able to conclusively shown the relation between work and heat, and therefore, that heat was a form of energy. What happened to the energy transferred by work to the water was the transformation to internal energy. The addition of heat to a substance increases the molecular activity and thus causes an increase in its internal energy.

"Although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form it appears simultaneously in other forms" [1]. This recognition of heat as an internal energy suggested to the formulation of the first law of thermodynamics, as the law of conservation of mechanical energy. It's conclusive to say that the first law applies to the system and its surroundings as represented in the Eq. (2.1) below:

$$\Delta(energy\ of\ the\ system) + \Delta(energy\ of\ surroundigs) = 0 \tag{2.1}$$

Energy of the system is related to the energy that can be stored as potential, kinetic and internal forms. Heat and work refer to energy in transit with the boundary between the system and its surroundings, these forms of energy can never be stored.

Assuming that in gas water heaters there is no transfer of mass in the boundaries with the surroundings, the system is said to be close. For this type of system, all the energy passing through the boundaries between system and surroundings is transferred as heat and work, Eq. (2.2) demonstrates it.

$$\Delta(energy\ of\ surroundigs) = \pm Q \pm W \tag{2.2}$$

Considering a constant mass of the system and if only internal-, kinetic-, and potential-energy, Eq. (2.3) describes it:

$$\Delta(energy\ of\ the\ system) = \Delta U + \Delta E_K + E_P \tag{2.3}$$

Rearranging Eq. (2.1) with Eqs. (2.2) and (2.3):

$$\Delta U + \Delta E_K + E_P = \pm Q \pm W \tag{2.4}$$

Closed systems are often subjected to processes that cause no changes in external potential or kinetic energy but only in internal energy. It is possible to reduce and simplify Eq. (2.4) to Eq. (2.5) considering also that in the system there will be no work done to the surroundings and that energy transferred to the surrounding as heat is positive.

$$\Delta U = Q \tag{2.5}$$

Equation (2.5) applies to processes involving finite changes in the system, the mass is constant.

Now is important to understand the meaning of internal energy. Internal energy is the energy contained by a thermodynamic system and its present on the molecules making up the substance of the system. The internal energy is a state function of a system, in other words, is an energy that only depends on the current state of the system, not on the way in which the system acquired that state. This energy can be called as specific internal energy which is internal energy per unit of mass. This led us to enthalpy, which is the internal energy plus the product of absolute pressure with volume, Eq. (2.6).

$$H = U + PV \tag{2.6}$$

As referred before, in our application it is considered that the kinetic- and potential-energy is very small compared with the others. It is also important to remind that pressure has a negligible effect on liquids unless very high pressures are applied. Thus Eq. (2.5) can be rewrite relative to enthalpy to accomplish Eq. (2.7).

$$\Delta H = H_f - H_i = Q \tag{2.7}$$

To this point it is considered a finite change system with constant mass, it is now consider a constant volume and constant pressure process, thus for a closed system of m mass Eq. (2.7) is replaced by:

$$Q = m\Delta H \tag{2.8}$$

Due to the system being mass flow variant it is possible to rewrite the Eq. (2.8) in Eq. (2.9) with mass flow variance.

$$\dot{Q} = \dot{m}\Delta H \tag{2.9}$$

The change in ΔH is positive for endothermic reactions, reactions that need heat, and negative for heat release exothermic process. In this system there will be the two types of processes, the heat is positive in endothermic process to increase the water temperature and the heat of combustion as a negative exothermic process.

2.2.2. Combustion

As known, the energy need to raise the water temperature comes from gas fuel. Thus, is very important understand correctly the process occurred during combustion and the heat produced. In this work it will be consider three types of fuel gas: methane (G20), butane (G30) and propane (G31). It's considered methane as being the principal gas present in natural gas to simplify equations.

Combustion is a chemical process that we usually call burning in which a substance reacts rapidly with oxygen and gives off heat. The substance is called the fuel, and the source of oxygen is called the oxidizer, in this case, air. To start the combustion some source of heat with a minimum energy of ignition is needed and it depends on the mixture of fuel/air. In addition, for the flame to spread there must be two limits in the mixture, the lower flammable limit (LFL) and upper flammable limit (UFL). Table 2.1 shows the values for the three gases.

Table 2.1 - Flammable limits and Auto ignition values of fuels

Substance (Fuel)	*LFL by Volume Air(%)*	*UFL by Volume Air(%)*	*Auto ignition (ºC)*
Methane CH_4	4.4 - 5	15 - 17	580
Butane C_4H_{10}	1.6	8.4	420 – 500
Propane C_3H_8	2.1	9.5 – 10.1	480

To describe correctly the combustion process it is need to know the chemical reaction referent to the process. It is known that the fuels are simple hydrocarbons and the oxidizer is air. Therefore the air composition must be known. Table 2.2 show the earth's atmosphere compositions at sea level.

Table 2.2 - Air composition

Gas	*% by Volume*	*Molecular Mass*
Nitrogen N_2	78.0880	0.028
Oxygen O_2	20.9495	0.032
Argon Ar	0.9324	0.040
Carbon Dioxide CO_2	0.0300	0.044

Attending to the percentage of gases constituent of air it is admit that air is only constitute by 21% of Oxygen and 79% of Nitrogen, in volume. Such simplification provides the possibility to write the chemical equation of the combustion for all simple hydrocarbons. Eq. (2.10) represents the stoichiometric mixture.

$$C_xH_y + \left(x + \frac{y}{4}\right)(O_2 + 3.76N_2) \xrightarrow{\Delta h} xCO_2 + \frac{y}{2}H_2O + 3.76\left(x + \frac{y}{4}\right)N_2 \tag{2.10}$$

In practice is known that when the stoichiometric quantity of air is supplied for the combustion the combustion will not be complete. Due to this behavior it is important to define richness is combustion. Richness is related to the air-fuel ratio AFR that is the ratio between the mass of air and the mass of fuel in the mixture. More useful, is the air-fuel equivalence ratio, λ, that is the ratio of actual AFR and stoichiometric AFR, this gives the richness of combustion, Table 2.3. Eqs. (2.11) and (2.12) demonstrate the AFR and λ calculation.

$$AFR = \frac{m_{air}}{m_{fuel}} \tag{2.11}$$

$$\lambda = \frac{AFR}{AFR_{stoich}} \tag{2.12}$$

Table 2.3 - Mixture richness

Mixture	λ
Stoichiometric	1
Rich	<1
Lean	>1

Rich mixtures are usually used for internal combustion engines and are not the aim for the gas water heaters. Rich mixtures also have ambient problems with products of combustion due to the generation of hydrogen and carbon monoxide, being this last one a serious atmospheric pollutant. Ideally lean mixtures produce the products present on Eq. (2.10) plus oxygen. For a lean mixture Eq. (2.10) can be rewrite as shown in Eq. (2.13).

$$\begin{gathered} C_xH_y + \left(\frac{1}{\lambda}\right)\left(x + \frac{y}{4}\right)(O_2 + 3.76N_2) \xrightarrow{\Delta h} \\ xCO_2 + \frac{y}{2}H_2O + \left(\frac{1}{\lambda} - 1\right)\left(x + \frac{y}{4}\right)O_2 + \left(\frac{1}{\lambda}\right)3.76\left(x + \frac{y}{4}\right)N_2 \end{gathered} \tag{2.13}$$

Defined the chemical reaction, it is of great interest know the heat produce during the reaction for each type of fuel and AFR. Heat of combustion of a fuel it's the absolute value of heat released during a complete combustion at standard conditions. This value is often presented in J/Kg, J/mol or J/m3 of fuel and has two values for the same fuel, the higher heating value and the lower heating value. This distinction comes from the physical state of water in the products of combustion. For gas fuels it is normally used the lower heating value.

Considering the gases involved in the process as ideal and the combustion at constant temperature and pressure is then possible to write the equation for the combustion heat. In Eq. (2.14) T_0 represent the temperature of the fuel, T_1 the temperature of the air, T_2 the temperature of exhaust gases and $\Delta h_0 = -LHV$.

$$\sum_i m_{Pi} C_{P_{Pi}} (T_2 - T_0) + m_{fuel} \Delta h_0 + \sum_i m_{Ri} C_{P_{Ri}} (T_0 - T_1) = Q_{Heat} \quad (2.14)$$

In gas water heaters the main objective is to release and transfer the maximum energy from the fuel to the water, thus is important to understand the efficiency of the combustion that can be calculated by Eq. (2.15).

$$\eta_{combustion} = \frac{|Q_{Heat}|}{LHV} \quad (2.15)$$

Usually the combustion efficiency is calculated with the absolute heat transferred to the fluid. This way is more relevant to know the heat exchanger efficiency that considers also the heat provided form the exhaust gases and products.

2.2.3. Heat Transfer

It is known from experience and by the zeroth law of thermodynamics that a hot object in contact with a cold one becomes cooler, while the cold object becomes warmer. Heat flows from a higher temperature object to a lower one, this leads to the conceptual idea that temperature acts as driving force for the transfer of energy as heat. More precisely, the rate of heat transfers from one body to another is proportional to the temperature difference between the two bodies. This is presented in equation (2.16).

$$\dot{Q} = \dot{m} c_p \Delta T \quad (2.16)$$

In heat transfer there are three ways of transfer, as demonstrate on Fig. 2.2: conduction, convection and radiation.

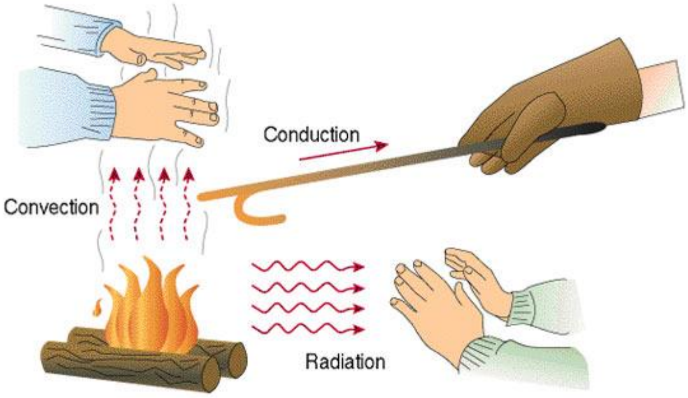

Figure 2.2 - Three ways of heat transfer: Conduction, Convection and Radiation

Conduction

Its basic fundament is the molecular and atom interaction with the neighbor atoms and molecules, transferring their energy to those. The normal heat transfer by conduction is present in solids. Eq. (2.17) represents the dependency of object shape and temperature difference. Fig. 2.3 is an example of heat conduction.

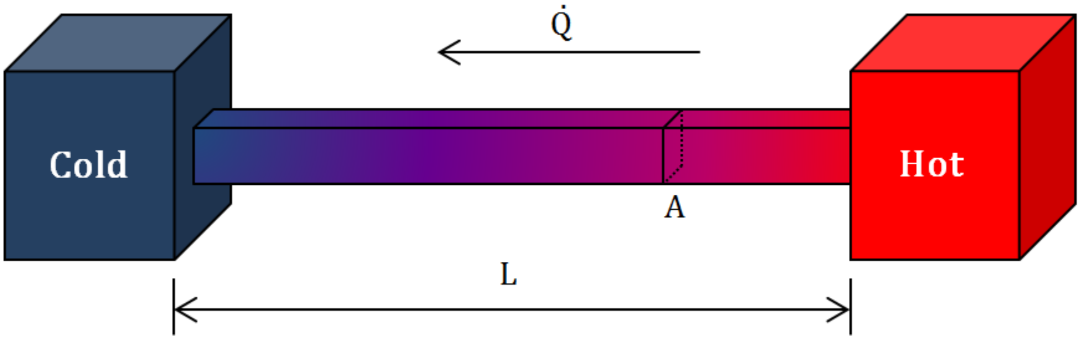

Figure 2.3 - Example of heat conduction

$$\dot{Q} = kA\frac{(T_{Hot} - T_{Cold})}{L} \tag{2.17}$$

Convection

This process is essentially the transfer of heat via mass transfer, represented by the Eq. (2.18). Convection is more common of heat transfer in liquids and gases. Convection can be natural or forced. Natural convection occurs due to changes in the flux density and forced when the streams and currents in the fluid are induced by external means (fans, pumps, etc…) increasing the heat flux thus the heat transfer coefficient h. Figure 2.4 gives an example of that exchange.

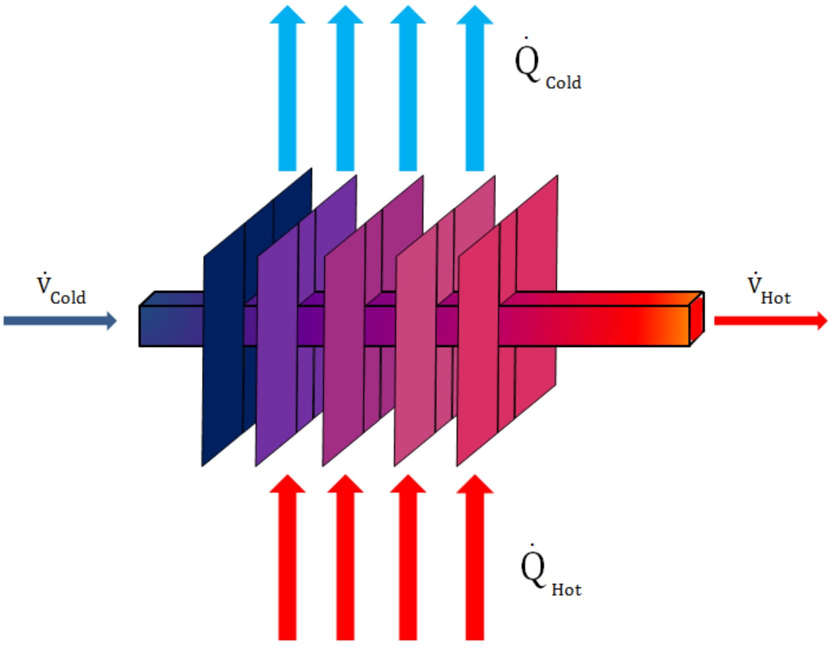

Figure 2.4 - Example of heat convection

$$\dot{Q} = hA\Delta T \tag{2.18}$$

An essential consideration in convection problem is to determine whether the boundary layer is laminar or turbulent. Surface friction and the convection transfer rates depend strongly on which of these conditions are present. For laminar boundary layer the fluid motion is very ordered and is characterized by the velocity which is normal to the surface. In turbulent boundary layer the fluid is in contrast very irregular and is characterized by velocity fluctuations. These fluctuations improve the heat transfer rates with the surface.

These effects vary the convection coefficient h, increasing for turbulent fluid flow and decreasing for laminar fluid flow.

Radiation

Thermal radiation is heat transferred by electromagnetic waves, this is the method humans receive heat from the sun, so it propagates without the presence of matter. Since there is an eye of sight between objects there will be transport of heat by radiation.

The energy emitted by real surfaces is then expressed in Eq. (2.19) where $\sigma = 5.76 * 10^{-8}\ W/m^2K^4$ is the Stefan-Boltzmann constant, ε is the surface emissivity in the range of $0 \leq \varepsilon \leq 1$ and T_s is the surface temperature. This equation provides a measure of how efficiently a surface emits energy relative to a blackbody.

$$E = \varepsilon\sigma T_s^4 \tag{2.19}$$

The equation for heat flux radiation is then presented in Eq. (2.20) and also depends on the temperature of the surface of the surroundings, T_{surr}.

$$\dot{Q} = \varepsilon\sigma(T_s^4 - T_{surr}^4) \tag{2.20}$$

2.2.4. Fluids

At this point is recognized that all the system operating methodology is based on fluids. The two of them are present in different states, water in liquid and fuel and air in vapor. It is then important to understand the fluid behaviors.

Liquid

Liquid is an almost incompressible fluid that molds itself to its container keeping nearly a constant volume independent of pressure.

The importance in liquid behavior is the dynamic response of water in pipes. Considering water as incompressible, based on the principle of mass conservation it is possible to make the following assumption: a flow imposed upstream will always be respected in the whole system, as long as the water can flow freely in at least one unconstrained pipe. This also implies that whenever the flow needs to be slip between two or more parallel pipes, the unconstrained flow distribution between them will be predefined in the model in terms of ratio. The sum of flow ratios of the number of slips should always be equal to 1, therefore respecting the imposed flow upstream. Another important consideration is that if the water flow can only go through one pipe and that pipe is constrained, then the flow is reduced directly in the whole system.

Those considerations are important when considering various methodologies for the control and must be always imposed otherwise the system would not respond to reality.

2.3. Control Methodology

In this work, it is proposed a control technique suitable to deal with linear and nonlinearities for a multivariable input and output (MIMO) system. The control technology will be focused in the combustion with the explicit aim of enhancing the user comfort, i.e., minimize the offset temperature.

Before introducing the methods it must be remark that poor behavior of a control loop cannot always be corrected by controller itself. As it has been studied, it is very important to understand these poor behaviors and they must be interpreted with the main goal in mind.

Poor process dynamics can be a result of a bad process design in the first place, resulting long dead times, long time constants, nonlinearities and inverse responses. Sensors and actuators have a key weight in the control. There are several reasons that may lead to a weak control loop like defective placing, badly mounted, bad dynamics, lack or too wide in resolution, imperfect accuracy, and so on.

“If a control loop is behaving unsatisfactorily, it is essential that we first determine the reason for this before tuning is attempted” [2].

2.3.1. MPC

Regarding to control methodology, model predictive control (MPC) has been successfully applied to a wide variety of industrial processes [3]. Model predictive control has been widely used for process control in chemical plants in which the controllers rely mostly on dynamic models of the process, often linear empirical models obtained by system identification. As study previously, a dynamic mathematical model combined with system experimental data will be implemented in Matlab/Simulink.

2.3.2. PID

The proportional integral derivative control is the most popular feedback controller used over the years in process industries. Its implementation is widely used in control architectures and has been successfully used for over fifty years. This is due its robust and easily understood algorithm that can provide excellent error cancelation despite the varied dynamic characteristics of process plants.

As the name suggests, the PID controller algorithm involves three different and separate constant parameters with its own time behavior: the proportional (P) depends on the present error, the integrative (I) on the accumulation of past errors and the derivative (D) is based on rate of change, thus predicting future errors.

There are many ways to configure different type of PID controllers as: P, I, PI, PD, PID, etc… More frequently used are the P, PI and PID controllers.

Proportional Controller

This is the simplest construction and tuning controller. It adjusts the output signal in direct proportion of the error, introducing then a steady state error. It is recommended to use in process having transfer functions with a pole at the origin or for transfer functions having a single dominating pole. The mathematical representation is shown in Eq. (2.21).

$$MV(t) = MV_{ss} + K_c e(t) \tag{2.21}$$

For a larger K_c the controller output will change proportionally. In the first term of the equation $MV(t)$ represents the error compensation output, the second term when the error $e(t)$ is zero the compensation assumes the steady state operating point MV_{ss} that should be calibrated to be in the setpoint when there is no error. Thus, if error is present K_c change proportionally the error compensation.

Proportional controller reduces error but does not eliminate it, then, an offset value will normally exist.

Proportional Integrative Controller

The addition of the integrative part corrects offset that may occur between the desired value and the process output. Although integrative alone does not exhibit steady state error, the PI provides a much faster steady state error cancelation.

PI controllers are widely used in process industries for slow variables like flow, pressure, level, etc… The mathematical representation is shown in Eq. (2.22).

$$MV(t) = MV_{ss} + K_c \left[e(t) + \frac{1}{T_i}\int e(t)dt\right] \tag{2.22}$$

The adjustable parameter apart from K_c is the integral time T_i .

Proportional Integrative Derivative Controller

This is the most well-known controller due to its universal applicability. It can be used in any type of SISO systems and, even in MIMO systems they are separate into several SISO.

What is new form the last controller introduced is the derivative part which action is to anticipate how the error will progress looking at the time rate of change of the controlled variables. The mathematical representation is shown in Eq. (2.23).

$$MV(t) = MV_{ss} + K_c \left[e(t) + \frac{1}{T_i}\int e(t)dt + T_D\frac{de(t)}{dt}\right] \tag{2.23}$$

The derivative action is characterized by the T_D time constant. Although in theory the derivative part should improve the dynamic response, if noisy signals are present in the control variable, noise will take control over the derivative part which will affect the steady state error. This way proper tuning of the PID controller is difficult and must be well done otherwise the system will fall into instability.

Equation (2.23) can be written in a simple sum of parts in which $K_P = K_c$, $K_i = K_c/T_i$ and $K_D = K_cT_D$. Eq. (2.24) is the parallel form of the PID controller.

$$MV(t) = K_Pe(t) + K_i\int_0^t e(\tau)d\tau + K_D\frac{de(t)}{dt} \tag{2.24}$$

PID Controller Tuning

As mentioned before, PID controllers must be tuned correctly otherwise they will make the system unstable. There are several methods to tune the PID gains as: manual tuning, Ziegler-Nichols, Software tools, Cohen-Coon, Tyreus-Luyben, etc... it will be presented the Ziegler-Nichols and Cohen-Coon methods.

Cohen-Coon

This method depends on experimental data and is suitable for first order lag systems. This method is not suitable for zero or virtually no time delay as we will see.

To compute the right gains, the Cohen-Coon provides a three step scheme. First it is needed to perform a step test to obtain the parameters of a PT_1 model. Is necessary to ensure that the element is at an initial steady state and after the step imposition the element settles at a new steady state. After that, a curve similar with Fig. 2.5 must be obtained.

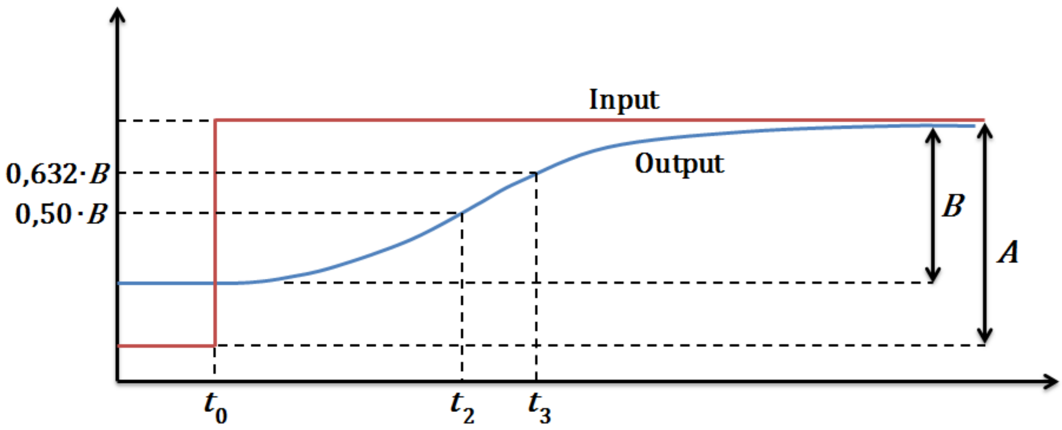

Figure 2.5 - Step response of a first order lag element

The second step is solely parameters calculations as shown in the equations below.

$$t_1 = \frac{t_2 - (ln\,2)t_3}{1 - ln\,2} \tag{2.25}$$

$$\tau = t_3 - t_1 \tag{2.26}$$

$$\tau_{delay} = t_1 - t_0 \tag{2.27}$$

$$K = \frac{B}{A} \tag{2.28}$$

$$r = \frac{\tau_{delay}}{\tau} \tag{2.29}$$

The final step consists in use the parameters calculated in the second step and apply them accordingly with table 2.4.

Table 2.4 – Cohen-Coon Tuning Gains

	K_P	K_P/K_I	K_D/K_P
P	$\frac{1}{rK}\left(1+\frac{r}{3}\right)$		
PI	$\frac{1}{rK}\left(0.9+\frac{r}{12}\right)$	$\tau_{delay}\frac{30+3r}{9+20r}$	
PID	$\frac{1}{rK}\left(\frac{4}{3}+\frac{r}{4}\right)$	$\tau_{delay}\frac{32+6r}{13+8r}$	$\tau_{delay}\frac{4}{11+2r}$

Ziegler-Nichols

This method is also heuristic. The gains calculated by this method are suitable for the parallel form of the PID controller. The process is also simple to achieve the results. First the integral and derivative gains are set to zero, then the proportional gain is increased until the output start to oscillate by itself. In the right moment when it starts to oscillate the proportional gain, that will be called the ultimate gain K_u , and wave signal period P_u have to be recorded to allow the final gains calculations.

Table 2.5 shows the gains calculation according to Ziegler-Nichols method.

Table 2.5 – Ziegler-Nichols Tuning Gains

	K_P	K_P/K_I	K_D/K_P
P	$\frac{K_u}{2}$		
PI	$\frac{K_u}{2.2}$	$\frac{P_u}{1.2}$	
PID	$\frac{K_u}{1.7}$	$\frac{P_u}{2}$	$\frac{P_u}{8}$

Although PID controllers are suitable for many applications given the user a satisfactory error control, they lack is some applications. This lack is due to its constant parameters. When process changes in some way the controller don't have the capability to understand and adapt to those changes. Thus PID alone doesn't allow the optimum control performance for process that requires some knowledge. Therefore the PID control should be used for error control.

2.3.3. Feedforward and Model Following

In basic close-loop control the feedback is used as a disturbance eliminator, for that it is necessary for the controller that should exist an error before the controller in order to take actions due to the error elimination. Feedforward provide a mechanism that measures disturbances before they have influenced the process. The principle implementation mechanism is shown in Fig. 2.6.

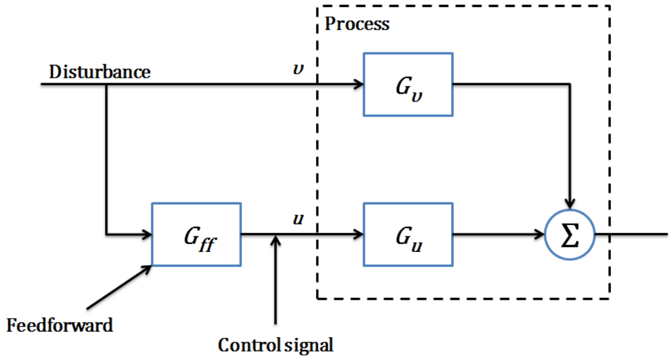

Figure 2.6 - Block diagram of a system with feedforward control from a measurable disturbance

Feedforward requires a mathematical model of the process, this way it will be much more sensitive to modeling errors than feedback control. Feedback may cause instabilities to the process while the feedforward does not add any stability problems. Thus, “To obtain a good control system, it is desirable to combine feedback and feedforward” [2].

One possible implementation methodology to combine feedback with feedforward is model following. Model following bases is methodology in setpoint response and this is achieved through a reference model that gives the desired response to setpoint changes. An example of model following using only simple feedback in shown in Fig. 2.7.

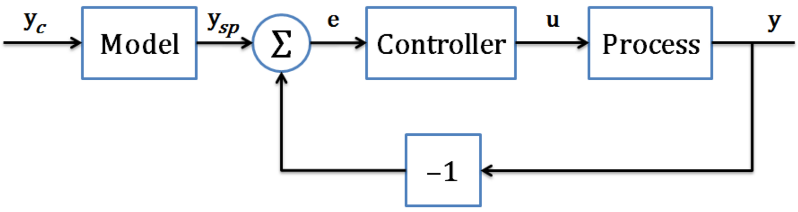

Figure 2.7 - Block diagram of a system based on model following

The reference model block is usually a dynamic system of first or second order. In this diagram configuration is important that the feedback signal is faster than the model response.

The previous diagram can be improved significantly by adding feedforward to the configuration of Fig. 2.7. Lets then show the improved configuration. Figure 2.8 has implemented feedback and feedforward. The signal coming out from the feedforward block, if the models are correct, will provide a signal to produce the desired output. The feedback will generate the compensation signal required for process disturbances. “Model following is used when precise setpoint following is desired…” [2].

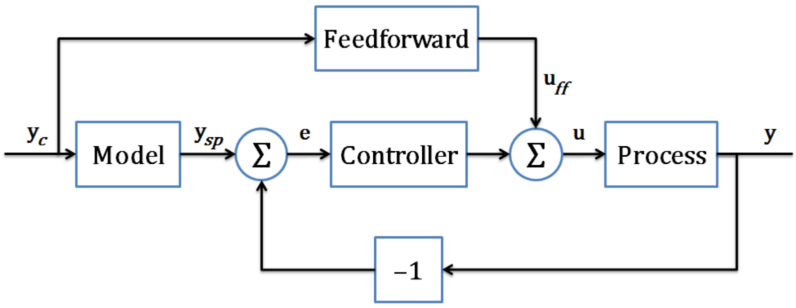

Figure 2.8 - Block diagram of a system that combines model following and feedforward from the command signal

2.3.4. Automatic Tuning and Adaptation

Combining the dynamics studies of the process with the methods for computing the PID parameters it is possible to obtain a method for automatic tuning [2]. Automatic tuning refers to methods that can change PID parameters depending on the system demand. For implementation of auto-tuning methodology it is first need to study correctly the process, after that the expert can understand which the system disturbances are, who generates them and how they will affect the system response.

“Industrial experience has clearly indicated that automatic tuning is a highly desirable and useful feature” [2]. Nowadays it’s possible to implement this methodology even if it is computationally weight. The auto-tuning methodology is based on two different approaches: the model-based, in which the tuning is based on developed system model and the rule-based approach in which the tuning is based on rules similar to a manually control overview.

Adaptive Control

Adaptive control is a methodology wherein the controller parameters are continuously adjusted in order to settle changes in process dynamics and disturbances. Adaptive control can be applied both in feedback and feedforward control, and particularly more advantageous for feedforward. There are two different ways to implement adaptive controllers: direct and indirect methods. The direct method is based on data acquired from the control loop and the indirect is based on recursive estimation of parameters from a model base of the process. Figure 2.9 shows indirect adaptive control in which its represented all the blocks necessary for the parameters computation.

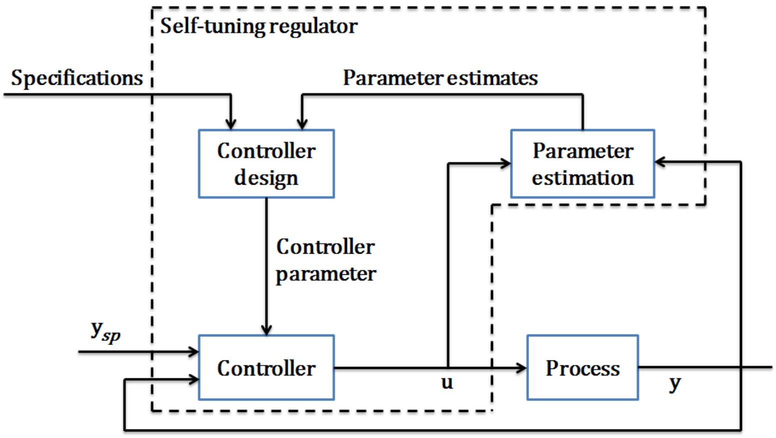

Figure 2.9 - Block diagram of an indirect adaptive controller

Automatic Tuning

As stated before, automatic tuning is tuned by demand from a user. Auto-tuning can be built inside the controller and can also be performed with external devices which can drastically simplify the use of the controllers. The main subject for this type of tuning is PID controllers which are widely used and are the most used type of controllers.

Gain Scheduling

This technique is fairly wide; it can deal with nonlinear processes, processes with time variations or situations where the operating conditions require such control change. For this method it is necessary to define the variables that will schedule the gains. This method is very effective for system whose dynamics change with the operating conditions.

Gain scheduling is a good alternative instead of adaptive methods. If the scheduling is based on a good knowledge of the process dynamics this method is advantageous and it can follow rapid changes. The key element for this technique is to find the suitable scheduling variables and this can take a substantial engineering effort. Figure 2.10 represents a block diagram of a system with scheduling gain and has it can be seen it has two loops in which the scheduling variable comes from the process but it can be chose as the control expert decides.

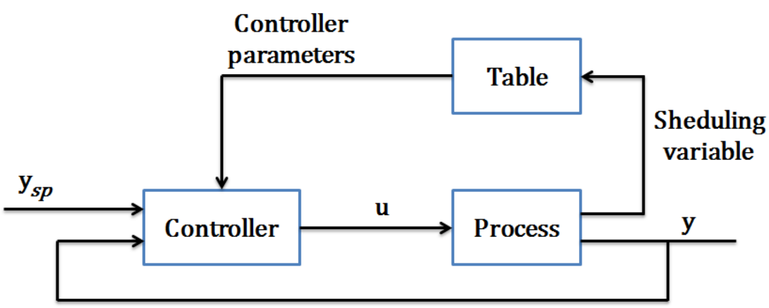

Figure 2.10 - Block diagram of a system with gain scheduling

2.3.5. Fuzzy

As mentioned before in subchapter 2.3.2., the lack in PID controllers referred to the knowledge and capability to adapt to different situations was one of the reasons that fuzzy control is presented in this dissertation. It's of great importance to understand the capabilities of real implementations of the fuzzy logic control.

The principal needs for fuzzy control implementation is due to the difficult task of modeling and simulate complex real world systems [4]. Even if a good model of the system could be implemented it is difficult to take into account all the complex responses that might appear. For that, fuzzy logic provides a formal methodology for representing, manipulating and implementing a human heuristic knowledge to the control system.

The fuzzy control architecture, Fig. 2.11, is the combination of four main components: the rule-base, that have the intelligence in the form of a set rules; the inference mechanism, evaluates which rules are more relevant for a given input; the fuzzification interface, is the component that understands the input and modifies it in order to the be interpreted and compared to the rules in the rule base and finally the defuzzification interface which converts the conclusions made by the inference mechanism and converts that conclusions to inputs to the process. We can say that a fuzzy logic controller is an artificial smart decision maker for real time closed loop systems. That smart component of the controller is as good as the rule base set. For that, the control engineer must gather as much and good information about the system.

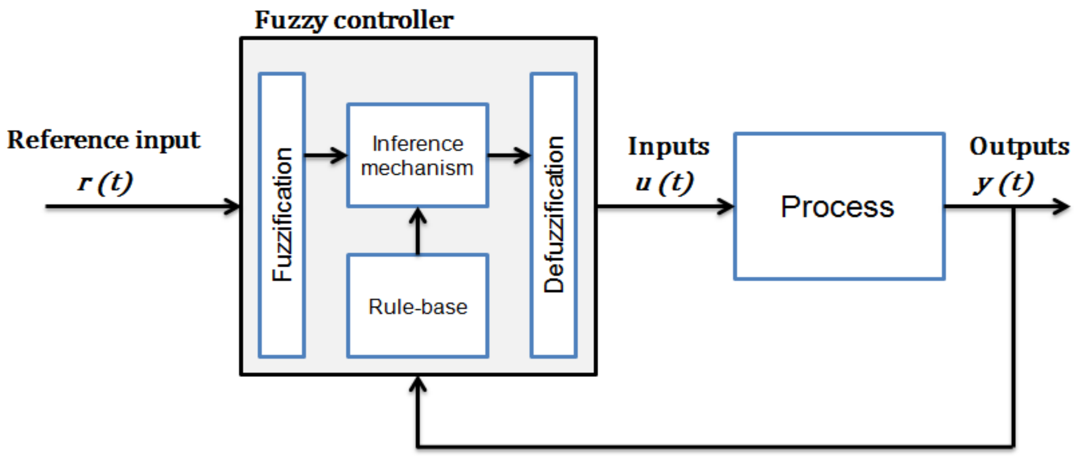

Figure 2.11 - Fuzzy architecture diagram blocks

Before the introduction of the essential parts it also important to understand the fuzzy sets and fuzzy set operations. A fuzzy set is a set in which the elements have degrees of membership, they in confront with classical set theory do not have a binary assessment. As in binary computation the set operations have the same operators as it can be seen in Eq. (2.25), (2.26) and (2.27) among other possible definitions.

$$Intersection: AND\ (A \cap B)$$
$$\mu_{A \cap B}(x) = min(\mu_A(x), \mu_B(x)) \tag{2.25}$$

$$Union: OR\ (A \cup B)$$
$$\mu_{A \cup B}(x) = max(\mu_A(x), \mu_B(x)) \tag{2.26}$$

$$Complement: NOT\ (\bar{A})$$
$$\mu_{\bar{A}}(x) = 1 - \mu_{\bar{A}}(x) \tag{2.27}$$

Let us then describe the four essential parts of the fuzzy controller.

Rule-base

After a well understanding of the system the expert controller engineer can describe which are the main inputs and its reference values, the outputs and make a linguistic description which will be loaded into the fuzzy controller. The linguistic description made by the expert is capable of relate the linguistic variables with which others, those relations are the artificial knowledge that are as good as the expert understanding of the system. Is then of major importance that rule-base set provides the better understanding of the process dynamics.

The rule-base part breaks down the system in descriptive linguistic that can be expressed as an IF-THEN rule. The general form of the linguistic rules is: **IF** premise **THEN** consequent. The premises are the inputs and the consequent the outputs. Using this approach it is possible to write a vast number of rules which are related with the values of each input. This capability leads to the next part of the fuzzy controller, the fuzzification.

Fuzzification

As known, the quantified linguistic rule-based itself is not possible to implement on computational programs, although it is possible to describe the premises in a way that the fuzzy controller can understand them. This is done by using membership functions.

Membership functions quantifies, in a manner, whether values of the premises belong to a certain set of values and hence it quantifies the meaning of the linguistic statements [4]. It is important to understand that each input can have different meanings, the way we quantify that meaning is direct with the type of membership function we consider. Let us consider the example of temperature quantification. If we say that between 21ºC and 25ºC is the comfort temperature of air and near that is more-or-less comfort the way to characterize this understanding is via the trapezoid membership function. If it is applied the sharp peak membership function it might be said something like: the comfortable air temperature is the almost exact 23ºC otherwise at the slightest difference it will not be comfortable. As these two examples there are more different ways to characterize the premises, this application depends on the control expert choice. Figure 2.12 shows some examples of membership functions for a different application case.

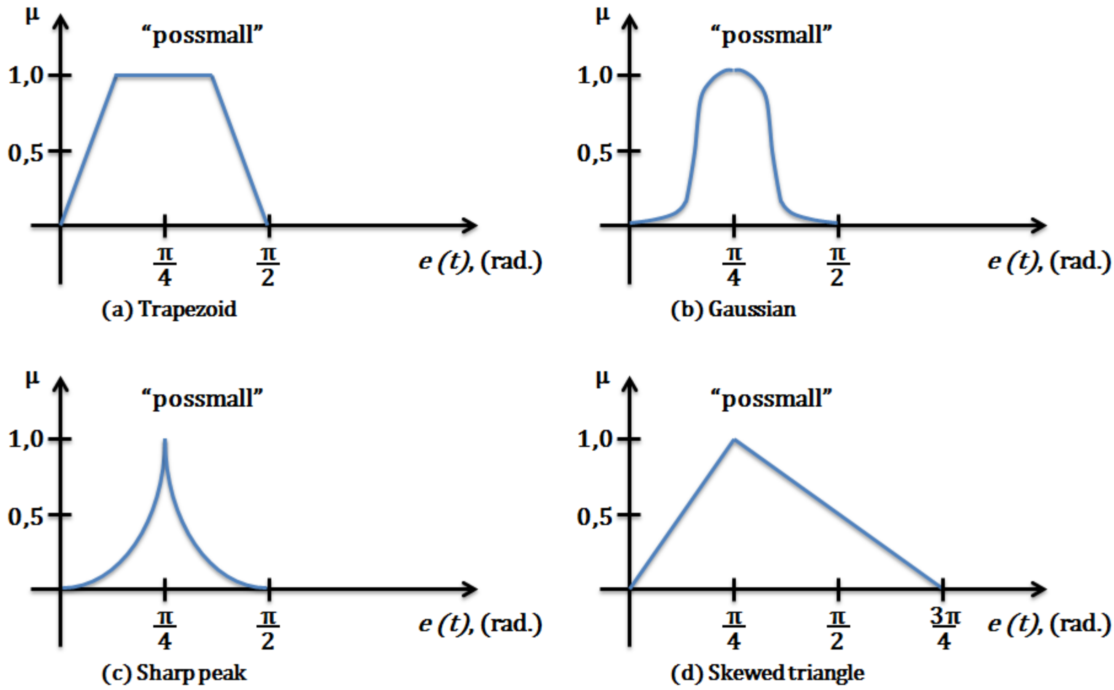

Figure 2.12 - Membership function examples [4]

Inference systems

The inference process generally involves two steps: first the premises of all the rules are compared to the system inputs to decide which rules have to be applied and in second the consequent is computed. For this mechanism two methods can be considered: Mamdani and Takagi-Sugeno.

Mamdani

In Mamdani models, the premises and the consequents are both fuzzy propositions. A Mamdani fuzzy model of a system is represented as shown in Eq. (2.28) in which x is input, A_i is a linguistic term associated with a membership, y is a output, B_i is also a linguistic term associated with a membership and n is the number of rules.

$$R_i : IF \ x \ is \ A_i \ THEN \ y \ is \ B_i \, , \quad i = 1,2, \dots , n \tag{2.28}$$

Takagi-Sugeno

In TS models, the premises and the consequents are crisp functions of the premises variables. A TS model of a system with n rules is represented with Eq. (2.29).

$$R_i : IF\ x\ is\ A_i\ THEN\ y_i = f_i(x)\,, \quad i = 1,2,\ldots,n \tag{2.29}$$

Defuzzification

The fuzzy inference mechanism results to a fuzzy output, this output does not indicate the exact value of the process overall output. This task of providing an exact value is accomplished by the defuzzifier which performs a fuzzy value to a crisp value conversion. This process is called defuzzification and there are a number of different strategies to implement this process.

For the TS inference system the defuzzification can be represented by the Eq. (2.30).

$$y = \frac{\sum_{i=1}^{n} y_i A_i}{\sum_{i=1}^{n} y_i} \tag{2.30}$$

In the case of Mamdani models, the aggregation and defuzzification processes are more distinct from the TS models. The more common defuzzification calculations methods are the center of gravity, first-of-maxima and mean of maxima.

Gain Scheduling with Fuzzy

One of the possibilities of fuzzy control is to provide a gain scheduler for the PID controller. Figure 2.13 demonstrates a block configuration tor this methodology. There are other possibilities of gain scheduling as reviewed before then is important to understand why to use fuzzy for this accomplishment. Fuzzy logic unlike the other methodologies has weighted and continuous gains. This method has the advantage of being more stable and a smother gain transient response.

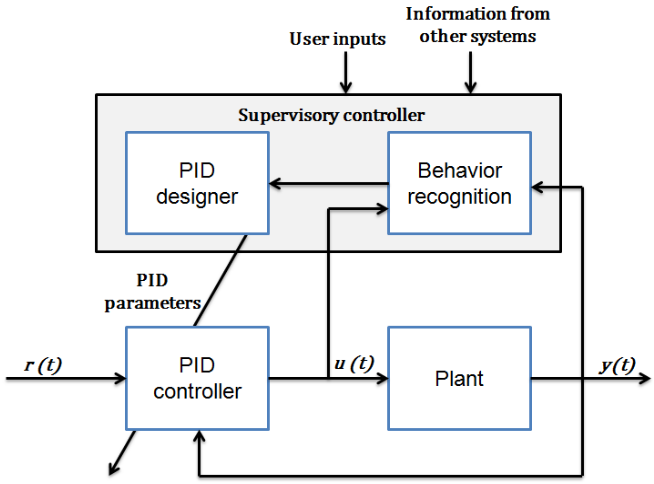

Figure 2.13 - Fuzzy gain scheduling control diagram blocks

2.4. Regulations

Standards are present in daily routine even people don't realize them. Standards have been around for at least as long as science exists, without them people wouldn't understand correctly and a great and unnecessary effort would be done to synchronize different people's work. A simple example of these standards is the paper sizes, for example this document in size A4.

As this dissertation is done in the EU is of great importance to follow some European standards (ENs). There are three European standardization organizations, CEN, CENELEC and ETSI that are officially recognized in the area of voluntary technical standardization. An EN is a document that sets some technical specification that must be achieved. ENs provide the improvement of market trade, reduction of costs also for the companies as for the consumers and enhances the performance and safety.

There are several types of standards. In this work it will be approach some for requirements and others for recommendations.

2.4.1. EN13203-1

This standard, the first of two parts of EN 13203, has been prepared by CEN and approved on 18 May 2006 and is applicable to gas-fired appliances for producing domestic hot water both for instantaneous and storage appliances with heat input not exceeding 70 kW and, if it have storage tank, it should not exceed 300 liters of storage capacity. In this work it is considered that there won't be a heat input above the maximum stipulated and even if the storage tank approach might be studied it won't be above the 300 liters.

This first part of this EN is of major importance for the main goal of this dissertation because is a standard for assessment of performance of hot water deliveries.

In this EN are presented the reference conditions, measurement uncertainties and test conditions that are well described in the papers for further information if needed.

More relevant is the characterization of the gas water heater. In general, domestic hot water appliances are characterized in two different ways: the specific hot water rate deliver under tapping test and to the quality of the domestic hot water produced.

Characterization according to the domestic hot water rates

The specific rate of a gas water heater appliance is calculated by the hot output temperature minus the cold inlet temperature and that difference should not be less than 30

Kelvin for the maximum water rate. The requirements and test need to characterize the appliance are described in [EN13203-1] chapter 5.2.

Characterization according to the quality of the domestic hot water produced

This classification is the most relevant for this dissertation. It represents the overall performance of the appliance measured by a given set of criterions with a specific weight for a final ranking calculation. These criterions are: waiting time, variation of the temperature according to the water rate, temperature fluctuation during delivery at a constant water rate, temperature stabilization time in case of variation of the water rate, minimum nominal water rate and temperature fluctuation under tapping.

According to those criterions presented, EN13203-1 presents table 2.6 where the performance factors and the weighting factors corresponding to each criteria are presented, thus by Eq. (2.27) it's possible to quantify the overall performance factor F, which can be interpreted as the comfort of the appliance.

$$F = \sum_{i=1}^{n} a_i f_i \tag{2.27}$$

Depending on the value obtained in Eq. (2.27) table 2.7 classifies the appliance.

Table 2.6 – Particular performance and weighting criteria [EN13203-1]

Particular performance criterion	*Particular performance factor f_i*				*Weighting coefficient a_i*
	0	1	2	3	
Waiting time	> 60 s	≤ 60 s	≤ 35 s	≤ 5 s	4
Temperature variation according to water rate	> 10 K	≤ 10 K	≤ 5 K	≤ 2 K	3
Temperature fluctuation at constant water rate	> 5 K	≤ 5 K	≤ 3 K	≤ 2 K	3
Temperature stabilization time	≥ 60 s	< 60 s	< 30 s	< 10 s	2
Minimum nominal water rate	> 6 l/min	≤ 6 l/min	≤ 4 l/min	≤ 2 l/min	1
Temperature fluctuation under tapping	> 20 K	≤ 20 K	≤ 10 K	≤ 5 K	1

Table 2.7 - Classification according to factor F

Label	*Value of the factor F*
_ _ _	< 14 points
* _ _	14 to 27 points
* * _	28 to 39 points
* * *	≥ 40 points with all particular factors ≥ 2

The test for classification according to performance are presented in [EN13203-1] in section 5.3.2.

2.4.2. EN13203-2

This is the second of two parts of EN13203 and was prepared and approved by CEN on 25 May 2006 and is applied for the same appliances has EN13203-1 presented previously. This EN regards to the assessment of energy consumption, it sets out a method to compare energy performances of different gas-fired appliances through a set of different tapping cycles.

All the reference conditions and measurement uncertainties are the same of each EN13203, for test conditions consult the respective standard.

For the tapping cycles are defined for each utilization specific normalized energy consumptions for a corresponding water flow rate. Table 2.8 shows that values.

Table 2.8 - Tapping types with energy and flow rates defined

Type of tapping	*Energy (kWh)*	*Hot water flow rates with temperature rise of 45 K (l/min)*
Household cleaning	0.105	3 ± 0.5
Small	0.105	3 ± 0.5
Floor cleaning	0.105	3 ± 0.5
Dish washing	0.315	4 ± 0.5
Dish washing 2	0.420	4 ± 0.5
Dish washing 3	0.735	4 ± 0.5
Large	0.525	4 ± 0.5
Shower	1.400	6 ± 0.5
Shower 2	1.800	6 ± 0.5
Bath	3.605	10 ± 0.5
Bath 2	4.420	10 ± 0.5
Shower plus bath	6.240	16 ± 0.5

The tapping cycles shown in table 2.8 are from [EN13203-2] on chapter 5. One of the goal of this standard is to determinate the daily energy consumption, for that, subsection 5.2.2 of [EN13203-2] presents the formulas to calculate the useful energy recovered by the water, the gas consumption, the electric energy if needed as auxiliary, water waste and energy consumption in stand-by mode.

Chapter 3

System Modeling

To understand the overall dynamic of the system a detailed and modulate approach needs to be done. Thus, a dynamic model of the entire gas water heater system will be implemented in the Matlab/Simulink environment. This model has the purpose to simulate various operation conditions giving us the possibility to develop the control method in a more precise way, being then easier to calibrate when implemented in real systems.

For the model let us consider the basic configuration presented before in Fig. 2.1 and then detach all the parts. As this document in more focused in the control method, some assumptions and simplifications are made in order to simplify the model. Nevertheless is always important to describe the physical structure of the system in order to have a more reliable model and thus a more realistic control.

In this chapter it is assumed that the sensors are all ideal for a simplified model.

System Overall

The general configuration of a basic gas water heater is already known, thus the dynamic subsystems with great importance are: the blower, gas valve, burner and water valves.

The flow components like the intake box and flue gas pipe are not considered in the modeled system.

Fig. 3.1 presents an overview about the modeled system with a new component named bypass valve that will be explained further and is also a water valve.

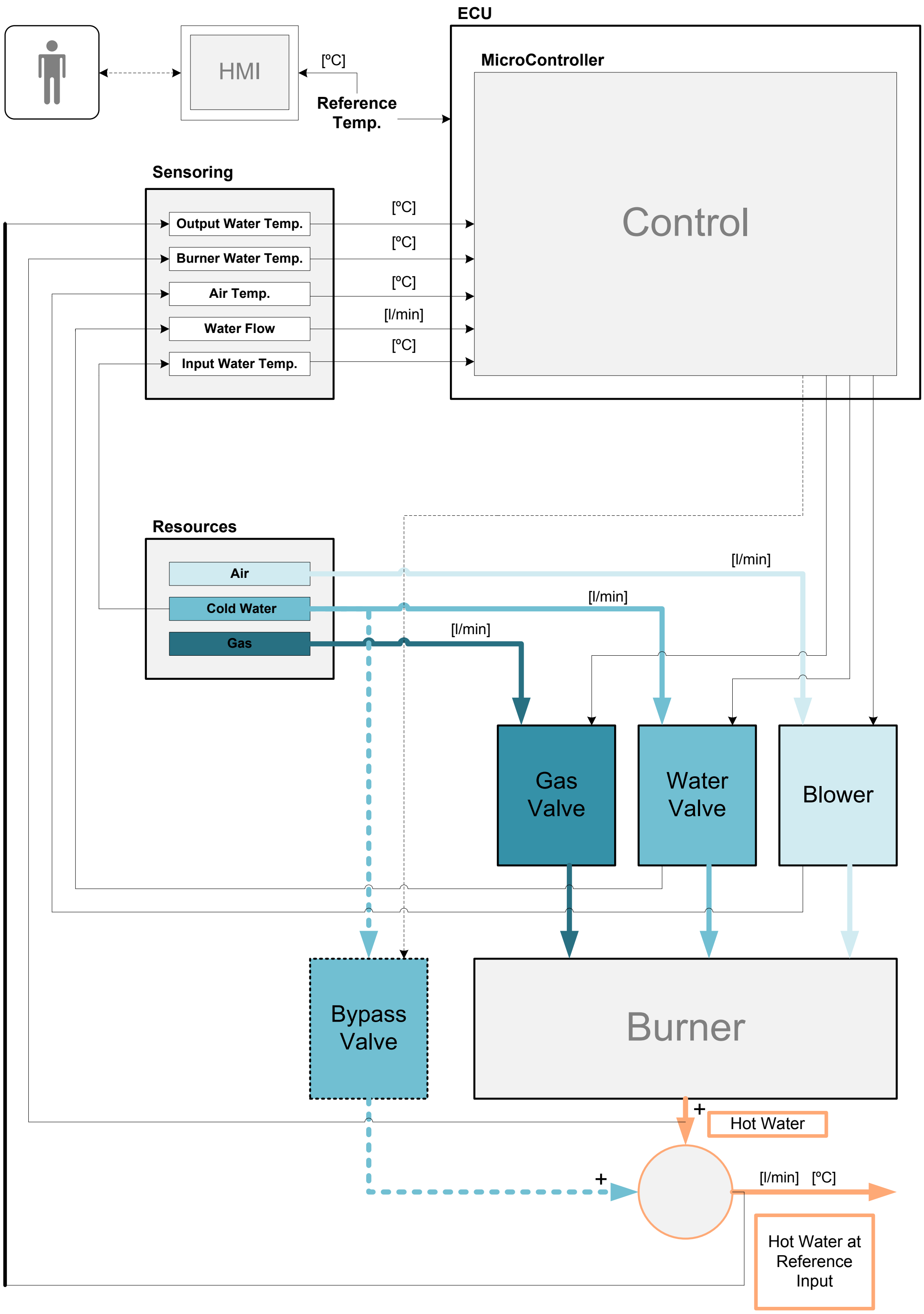

Figure 3.1 - System overview diagram

In the following are described the characteristics of each subsystem and how they were implemented. Also simulations with realistic values are presented.

3.1. Blower

As heat demand differs, different air flow is necessary to provide in order to have the right amount of oxygen for combustion. The most important characteristic of the blower is the relation of pressure rise with air flow at different fan speeds. Usually fan suppliers provide the fan curves for a limited fan speeds. It is then necessary to know the right pressure rise and air flow for a specific fan speed. This can be achieved using the fan laws.

Fan laws are useful for geometrically similar fans using dimensionless constants which can be calculated. Thus let describe these fan laws. Eqs. (3.1), (3.2) and (3.3) represent flow rate law, pressure rise law and power law respectively [10].

$$C_{flow} = \frac{\dot{V}}{D^3 N} \tag{3.1}$$

$$C_{pres.} = \frac{\Delta P}{\rho D^2 N^2} \tag{3.2}$$

$$C_{power} = \frac{W}{\rho D^5 N^3} \tag{3.3}$$

Assuming the air incompressible and no change in the fan diameter, D, it's possible to rewrite the Eqs. (3.1), (3.2) and (3.3) in a way that given one fan curve by the supplier it's possible to know the pressure rise versus air flow for any given fan speed. Equations (3.4), (3.5) and (3.6) makes it possible to trace the graph of Fig. 3.2 and then know the specific curve of the blower.

$$\dot{V}_B = \dot{V}_A \left(\frac{N_B}{N_A}\right) \tag{3.4}$$

$$\Delta P_B = \Delta P_A \left(\frac{N_B}{N_A}\right)^2 \tag{3.5}$$

$$W_B = W_A \left(\frac{N_B}{N_A}\right)^3 \tag{3.6}$$

The intersection of the specific curve with the pressure rise curve defines the operating point. When the system resistance changes the operating point also change. Thus is important to know one point for a specific fan speed to trace the specific curve.

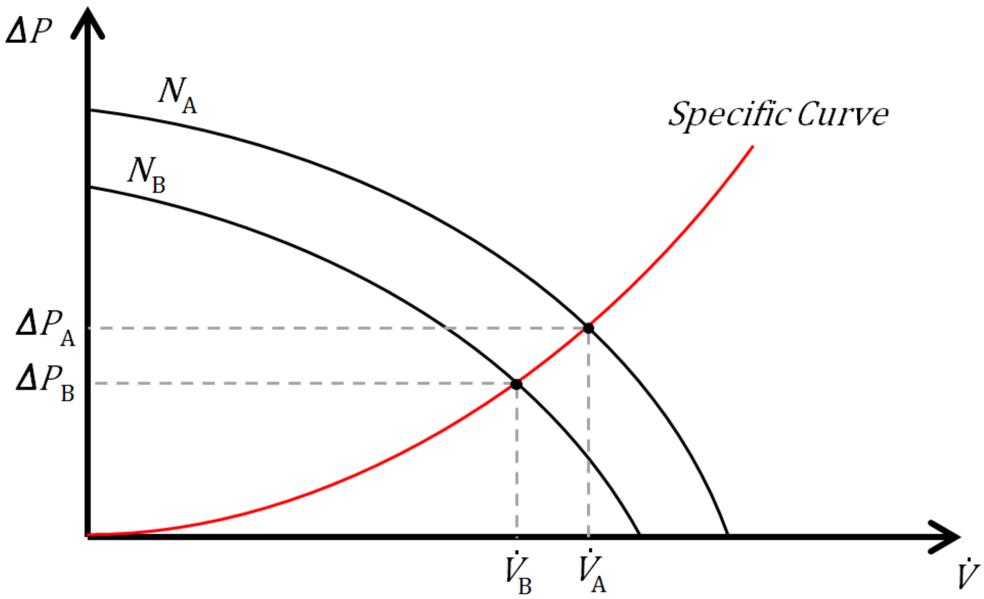

Figure 3.2 - Pressure rise versus air flow graphic

Another important factor for air flow calculation is the inlet air density. This value can be estimated assuming the air as an ideal gas. Combining the ideal gases equation (3.7) with the density equation (3.8) and molar mass equation (3.9) it is possible to get Eq. (3.10) and it's visible that the most relevant factors are temperature and pressure which change in time. Considering that the system will operate at constant ambient pressure the only influence factor is temperature.

$$PV = nRT \tag{3.7}$$

$$\rho = \frac{m}{V} \tag{3.8}$$

$$n = \frac{m}{M} \tag{3.9}$$

$$\rho = \frac{MP}{RT} \tag{3.10}$$

Now that the inlet air density change with temperature is possible to compute, applying Bernoulli's equation for fluids it's possible to compute the air flow variation with inlet air temperature variation.

Considering that the air density used to calculate the specific curve is known we can apply Eq. (3.11).

$$P_{ref} + \frac{1}{2}\rho_{ref}v_{ref}^2 = P_{new} + \frac{1}{2}\rho_{new}v_{new}^2 \tag{3.11}$$

Let us consider $P_{ref} \cong P_{new}$ and knowing that $\dot{V} = vA$, with constant area Eq. (3.11) can be written as Eq. (3.12).

$$\dot{V}_{new} = \frac{\rho_{ref}}{\rho_{new}} \dot{V}_{ref} \tag{3.12}$$

Dynamic Response

Real blowers have specific response curves. This is due to mass inertia and friction losses. Is then of major importance to know how the blower accelerates to its reference speed. With the help of characteristic transfer function it's possible to model the time variance of the system [7]. Experimental data show that the start-up response of the blower is very similar to a first order lag element (PT_1) show in Fig. 3.3. Thus is possible to describe the blower by the general step response function of Eq. (3.13).

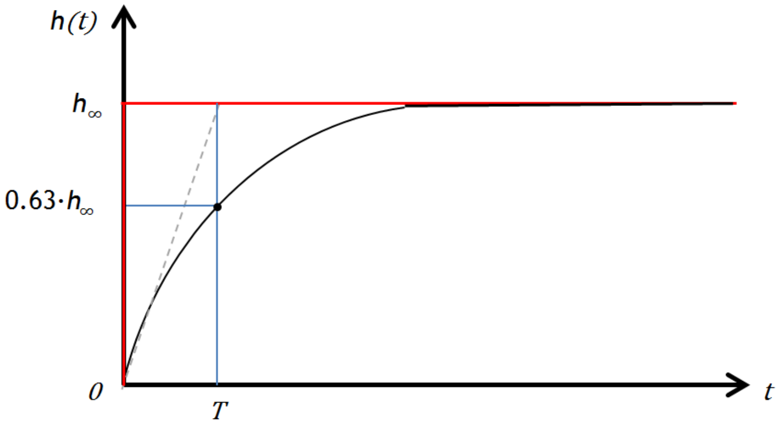

Figure 3.3 - Step response of a PT_1 element

$$h(t) = h_\infty \left(1 - e^{-t/T}\right) u(t) \tag{3.13}$$

The corresponding transfer function in frequency domain is written as Eq. (3.14).

$$G(s) = \frac{k}{1 + Ts} \tag{3.14}$$

To estimate the time constant T of the blower transfer function, a step signal input from zero speed to a fixed value speed must be measured in order to visualize the time that the response signal needed to reach approximately 63% of its final value Fig.3.3.

With all this methods it's possible to implement the blower behavior in Matlab/Simulink.

Implementation

In order to estimate the rise time, measures where made as shown in Fig. 3.4. With those values it was made an initial estimation. During simulations various values for times where tried to approximate to reality.

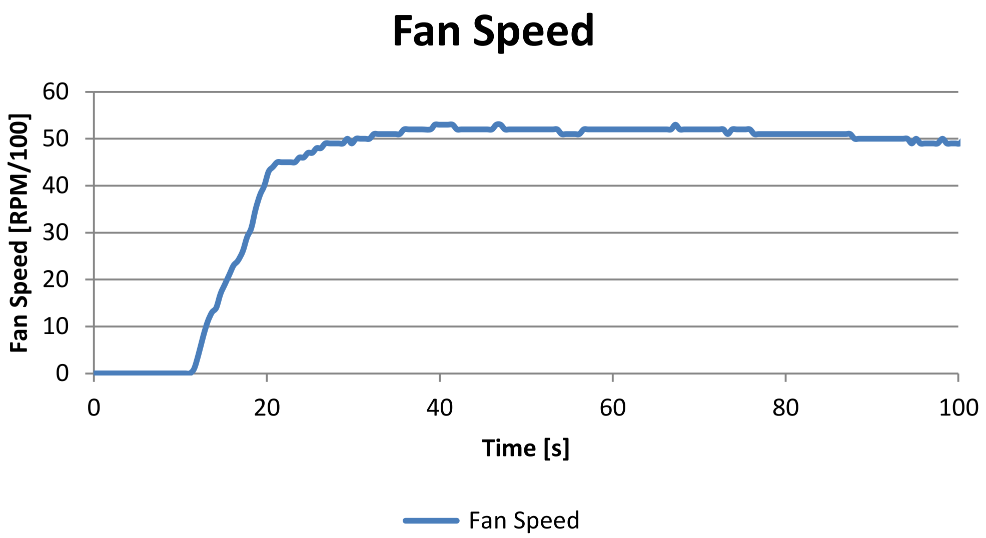

Figure 3.4 - Fan Speed on the blower step response time

The Matlab/Simulink implementation of the blower is here represented in Fig. 3.5, 3.6 and 3.7.

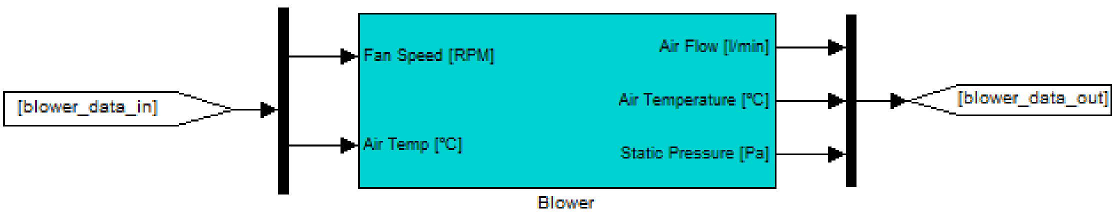

Figure 3.5 - First layer blower block

Above is presented the simplified block of the blower. Figure 3.6 is a second layer in which is presented the response delay and the block “Blower” which has the specific curve of the blower.

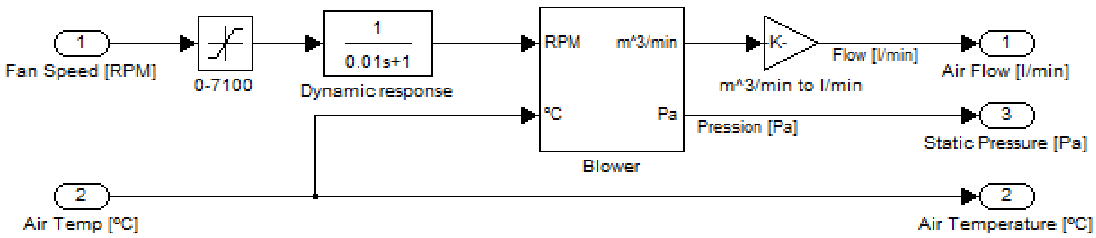

Figure 3.6 - Second layer block diagram of the blower

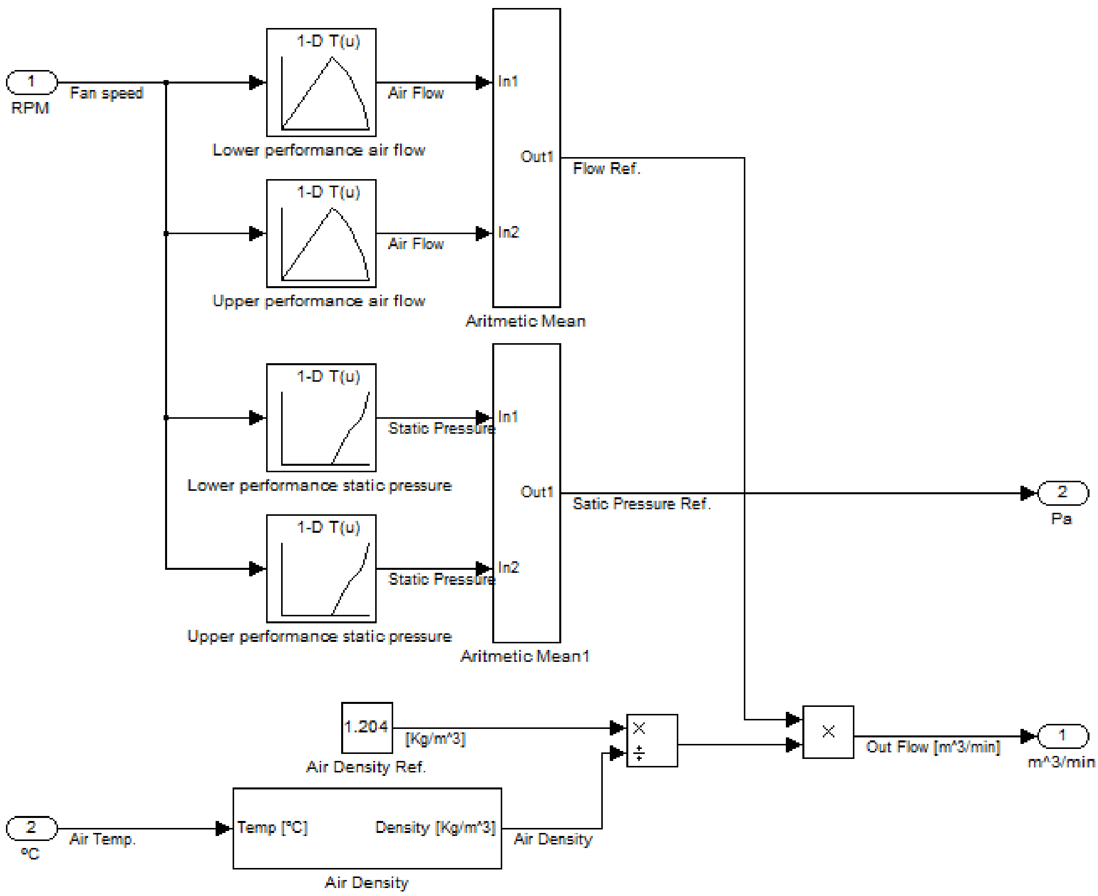

Figure 3.7 - Third layer block diagram of the blower

As stated previously, the air temperature changes the air flow. Figure 3.7 has implemented these variable behaviors with the “Air Density” block. Also altitude could be considered, but in this model it was considered sea level simulation. The lookup tables have the specific behaviors for a particular product. The supplier gives a lower and upper performance values this is why there are two lookup tables for each variable.

3.2. Gas Valve

The gas valve is one of the most important actuators present in the system. It’s from it that energy in form of fuel is delivered to the burner in a controlled way. Thus is very important to provide the exact gas flow to the burner.

Gas valves can be electromagnetically or step-motor driven which provides them different quality in terms of accuracy, reliability, longevity, security, etc. Suppliers provide the pressure rise exactly at the output of the valve related with the command signal given to the valve actuator. This relation can be also acquired by experimental procedures with different valve configuration and different drive signal commands [8].

Pulse with modulation (PWM) is the more common way to drive these valves but to simplify the modeled valve behavior pretended is a current command signal vs. gas flow. In order to find the relation of pressure rise in the valve vs. gas flow to the output we will consider the model of Fig. 3.8.

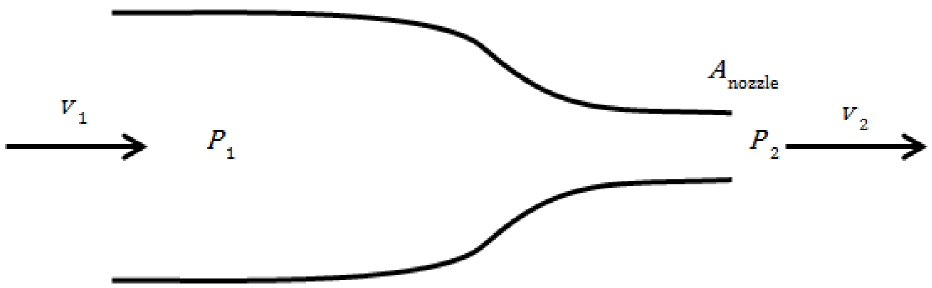

Figure 3.8 - Gas valve output nozzle model

The Bernoulli equation describes the variation in flow through the gas valve. In Eq. (3.15) it is considered the (1) as the direct output of the valve actuators and (2) as output space where the gas flow will be injected.

$$P_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g z_1 = P_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g z_2 \tag{3.15}$$

Eq. (3.15) can be simplified if it is assumed a horizontal flow $z_1 = z_2$ and a constant fluid density $\rho_1 = \rho_2 = \rho$. We also consider that the speed of the gas in (1) is much slower than in (2), $v_1 \ll v_2$ then $v_1 \approx 0$, so it is feasible to obtain Eq. (3.16) from which we can calculate indirectly the output flow.

$$P_1 = P_2 + \frac{1}{2}\rho v_2^2 \tag{3.16}$$

For the present nozzle shown above in Fig. 3.8, it is now possible to estimate the gas flow as a function of pressure gradient $\Delta P = P_1 - P_2$ with a specific and constant cross-section nozzle area. As the system is suitable for different types of fuel gas, Eq. (3.17) is also fuel gas density dependent.

$$\Delta P = \frac{1}{2}\rho_{fuel}\left(\frac{\dot{V}_2}{A_{nozzle}}\right)^2 \tag{3.17}$$

$$\dot{V}_2 = \sqrt{\frac{2\Delta P A_{nozzle}{}^2}{\rho_{fuel}}} \tag{3.18}$$

Dynamic Response

Since the fuel is not injected directly in the burner it will need to cover a distance from the nozzle to the direct output into the burner. Thus, there will be a delay in the delivery of the gas that can be calculated according to the model in Fig. 3.9.

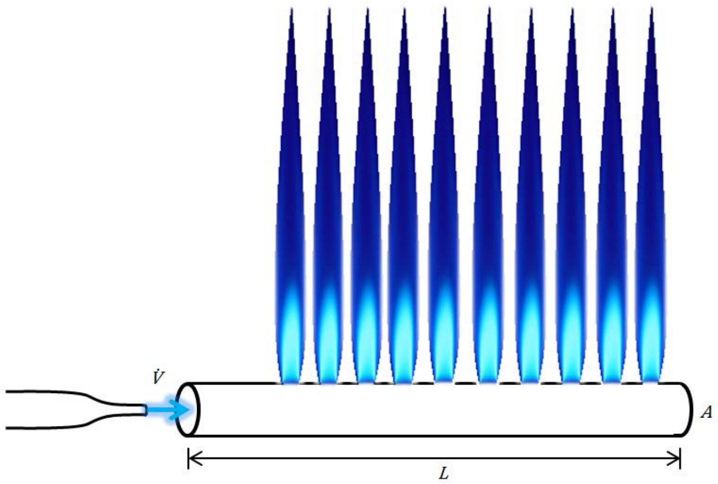

Figure 3.9 – Model of gas delivery to the burner

Assuming this configuration, a cylindrical tube with a length L and cross-section A, to calculate the delay as a function of the fuel gas flow $\dot{V}$ it is used Eq. (3.19).

$$t_{delay} = L\frac{A}{\dot{V}} \tag{3.19}$$

At this point the need to go further in the understanding of the gas valve operation is important. Let's consider Fig. 3.9 as a single fuel supplier to the burner, then consider it as many as wanted and divide them by sections. Fig. 3.10 shows a possible implementation of a burner plate. The burner plane is divided in three sections, A, B and C. These represent the three configurations possible of fuel gas deliver. The possibility inherent with this configuration is to provide a wide minimum to maximum range of combustion. For this possibility, the gas valve has two on-off actuators which can provide the three operation conditions.

The change between on and off for each section has a time delay inherent and some particular considerations. These will be studied further.

Implementation

This part of the simulation was considered a key element for the right performance of the model. As stated before, the burner is divided by section/segments. Fig. 3.10 shows a possible configuration of it. The important understanding is the minimum and maximum power that each section/segment can deliver and the time delay that takes to ignite and turn off the flame.

The configuration also have the particularity that only section A has the ignition spark, this means that all the other sections need that previously one of the other was already burning, in order to propagate the flame. This is what influence the time delays explained before.

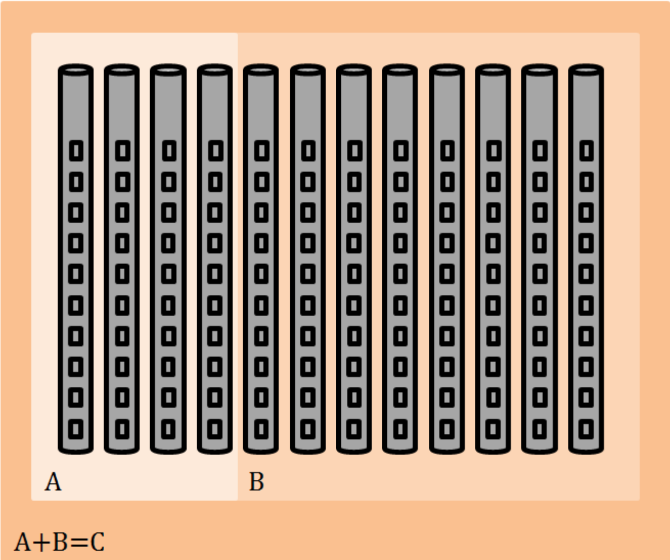

Figure 3.10 - Burner plate configuration

In Matlab/Simulink the gas valve block layers were the following shown in Fig. 3.11, 3.12 and 3.13.

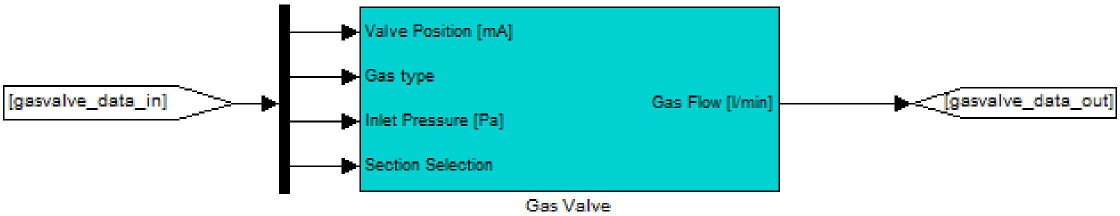

Figure 3.11 - First layer of the gas valve

This first layer shown above is the simplest block for the gas valve. It has the possibility to configure the type of gas that is being used with input "Gas Type". The section selection represents the dynamic explained before regarding the segmentation process.

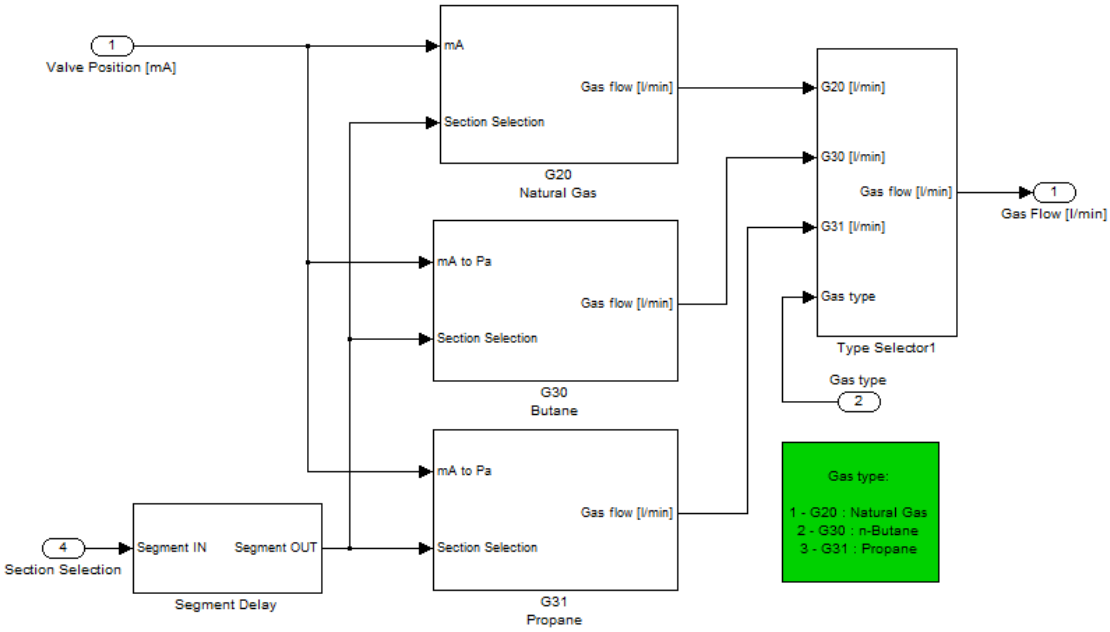

Figure 3.12 - Second layer of the gas valve; type of gas and section/segment selection

Due to the size of “Segment Delay” block it will not be shown in this document the inside layer but it follows specific time delays.

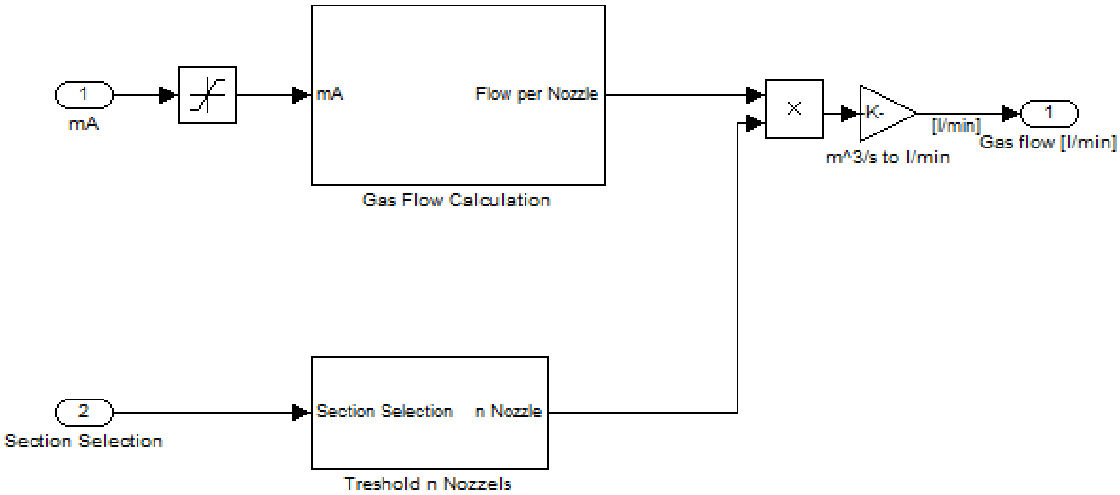

Figure 3.13 - Third layer of the gas valve; time delays and gas flow estimator for G20

It is inside of “Gas Flow Calculation” block in Fig. 3.13 that the equations regarding gas flow estimation are implemented. There are also functions implemented for the delay time of the gas propagation. This can be used also as a tuning block for unpredicted time delays in the gas valve.

3.3. Water Valve

Water valves aim is to suppress or regulate water flow in the system with a consequent change in pressure. Bernoulli’s equation demonstrates that relation as shown in Eq. (3.15). The importance of the water valve model will be further explained in the implementation chapter. In Fig. 3.14 is shown an example of a water valve.

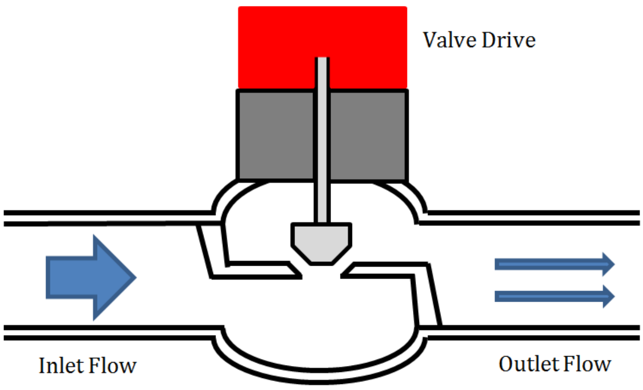

Figure 3.14 - Example of a water valve

The principal characteristic of valves is fluid flow vs. valve opening. Fig. 3.15 illustrates three possible response curves. In then important to know in which of those responses our valve is operating.

For this work it will not be consider the drive signal, assuming that there is already a command signal processor for those valves.

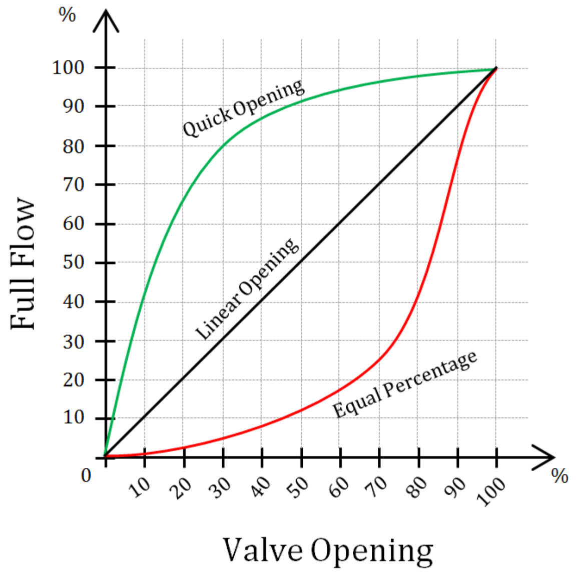

Figure 3.15 - Characteristic curve of valve opening

Implementation

For the water valves no time delay is considered. It is then a simpler model than the other ones. The block of this actuator is important to be totally independent to enable the use of the same in totally different situations. Figure 3.16 and 3.17 shows the implementation blocks.

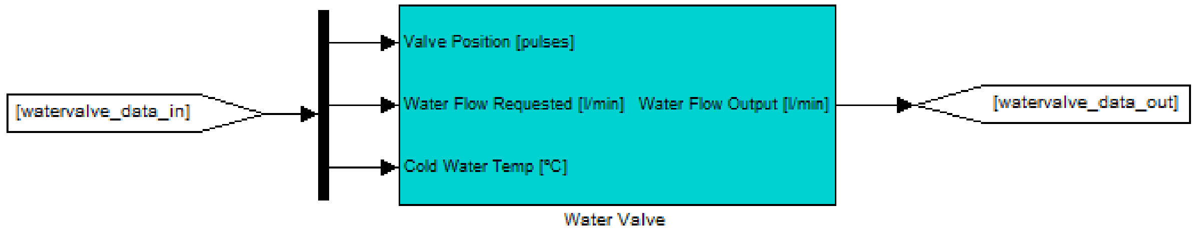

Figure 3.16 - First layer block of water valve

The “Water Valve” block has inside a lookup table with the characteristic curve of the valve opening or closing, depending on the valve configuration. In this model it is considered a specific closing curve; this means that in standby the valve is fully open. To perform the flow restriction it is used a saturation block with variable saturation values. No change in pressure is calculated.

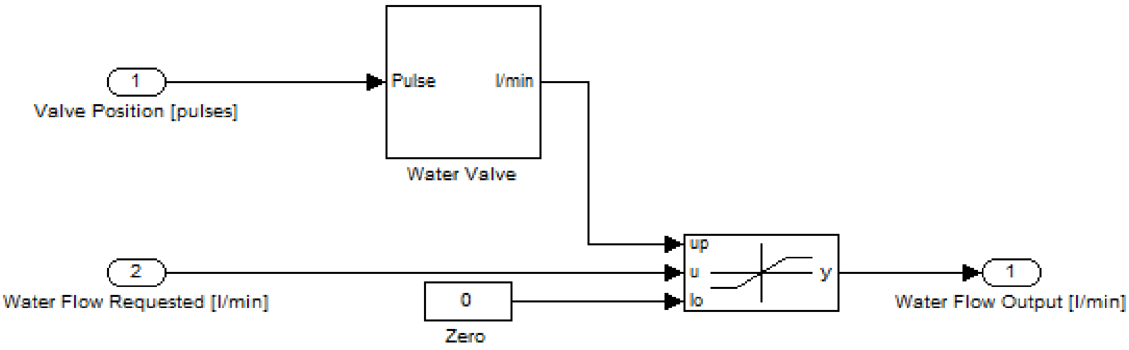

Figure 3.17 - Second layer block of water valve

3.4. Burner

It is in the burner/combustion chamber that the fuel mixes with air and where the combustion takes place. As the source of energy comes from the combustion, in order to calculate the heat transferred to the water it is important to model the right dynamic and make some assumptions.

As study in chapter two, the principal heat transfer present in the burner is convection. Conduction and radiation are considered not so relevant for the model, providing then a simpler model of the heat exchanger. Conduction is the heat transfer between the heat provided by convection and heat transferred to the water. Figure 3.18 shows that action. Those considerations in fact are related to: $R_{conv.4-3} \ll R_{rad.4-3}$ and the high k_{copper} . Being then the copper mass of the heat exchanger low, thus a low $R_{cond.3-2}$ is obtained.

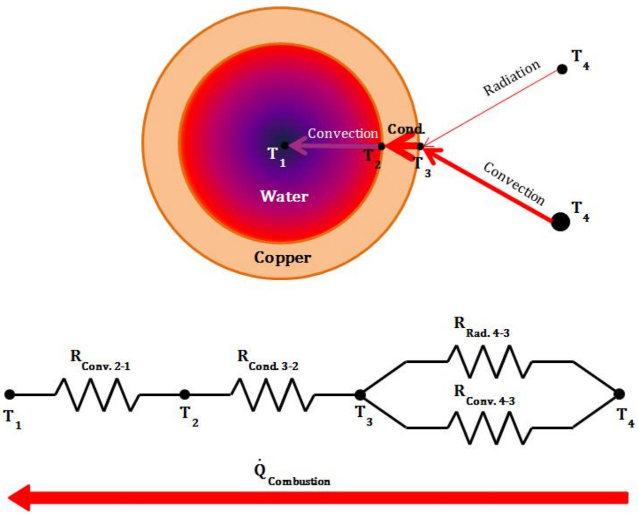

Figure 3.18 - Heat transfer from the flame to the burner

The heat exchanger is a physical device similar to a radiator, but in the reverse operation. Therefore is highly important to understand its dynamics and its performance. Due to the high complexity of heat transfer calculation and modulation. Experimental data will be gathered in order to make a mathematical approximation for its dynamics and performance.

The burner can be divided into the following sections: the air ventilation with gas injection into the combustion chamber providing the $\dot{Q}_{combustion}$, the combustion chamber and the heat exchanger that transfers the heat form the flame to the water. Figure 3.19 simplifies all those parts in one single representation. In terms of heat transfer by the equation of conservation of energy Eq. (3.20) simplifies the whole physics processes of the device.

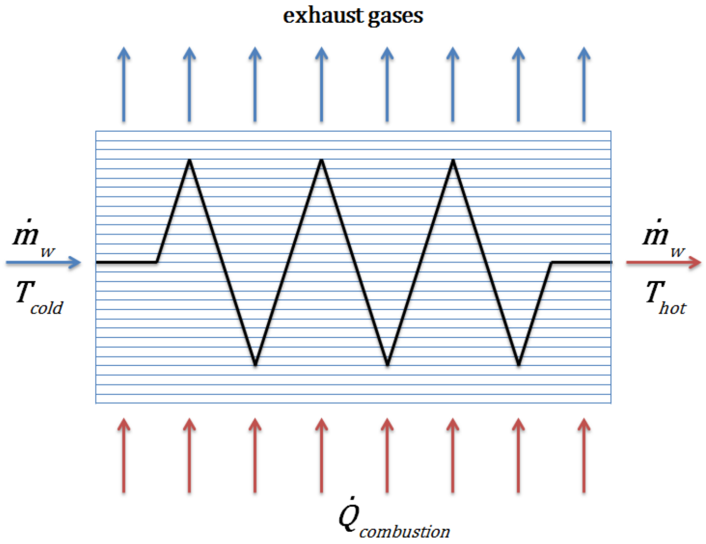

Figure 3.19 - Heat exchanger representation

$$\dot{E} = \dot{Q} + \sum_{IN} \dot{m} C_p \Delta T - \sum_{OUT} \dot{m}\, C_p \Delta T \qquad (3.20)$$

For equations simplifications it is considered the transfer of heat between the flame and water without losses, then it's possible to compute Eq. (3.20) as Eq. (3.21).

$$\dot{Q} = \dot{m} C_p (T_{hot} - T_{cold}) \qquad (3.21)$$

Implementation

For this part of the appliance experimental data was acquired and interpreted. As can be seen in Fig. 3.20, the time response of the heat exchanger is similar to a PT_1 element.

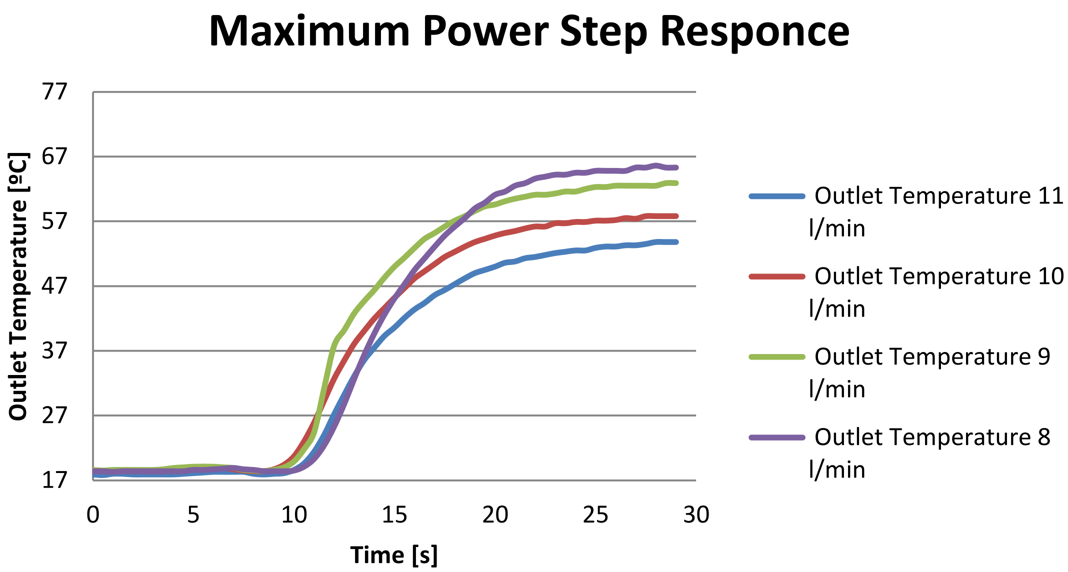

Figure 3.20 - Step response of heat exchange for maximum power of the appliance for different water flows

The rise time varies with the mass of water flow as expected. For the implementation those considerations where taken into account, also that the system was without heat lossless and efficiency changed with the particular segment active in the burner. Figure 3.21 represents the implementation general block for the combustion.

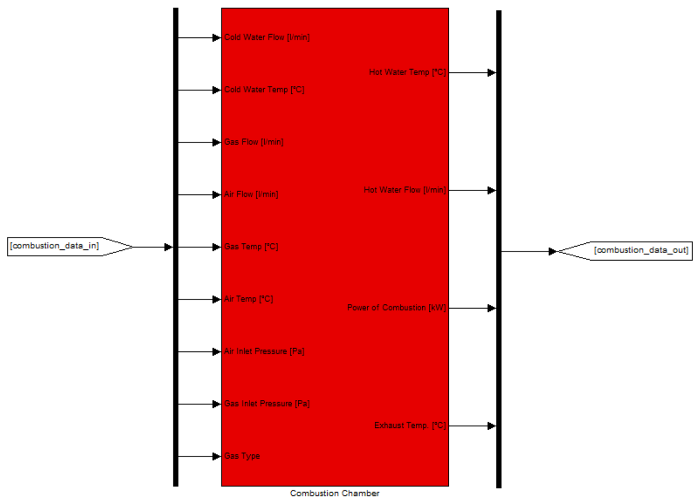

Figure 3.21 - First layer of the combustion chamber block

Figure 3.22 represents the second layer inside the combustion chamber block. “Heat Exchanger” block simulates the dynamics studied before. The “Combustion Heat” block calculates the power of combustion depending of several inputs as show in the image, respectively: gas flow, air flow, gas type, gas temperature, air temperature, air inlet pressure, gas inlet pressure and water heat power transferred.

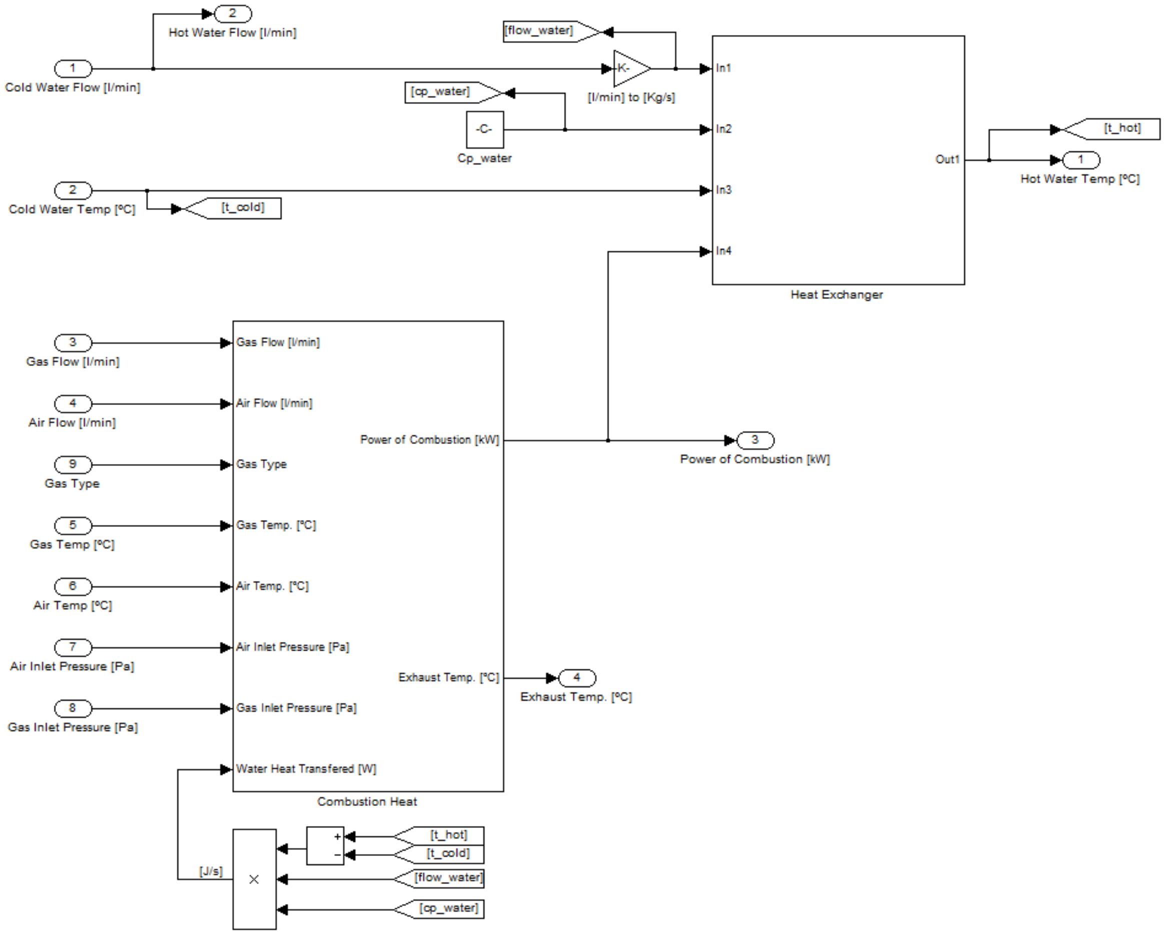

Figure 3.22 – Second layer of the combustion chamber

Figure 3.23 shows the inside of the “Combustion Heat” block and demonstrates the structure approach for the different type of gases. Changing the “Type selector” it is possible to calculate the combustion heat for different percentage of a mixture with the three main fuel gases.

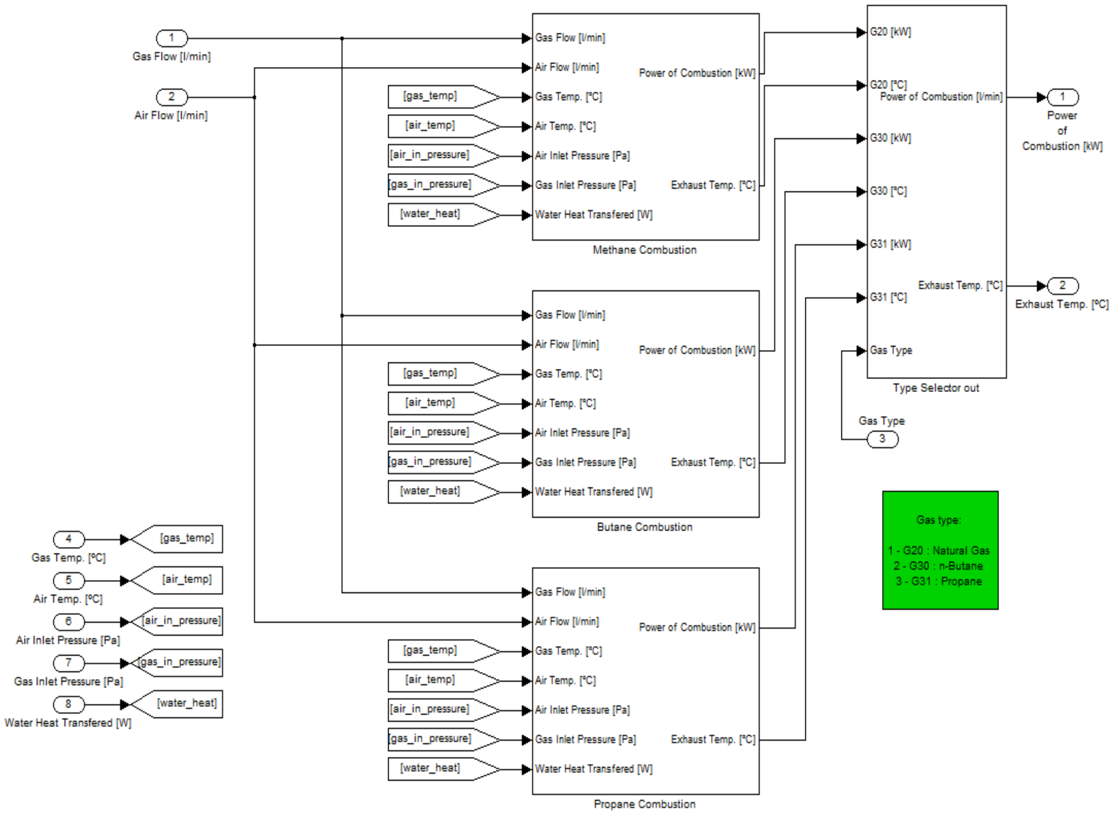

Figure 3.23 – Inside of the combustion heat block

3.5. Model validation

To ensure control algorithms with accurate dynamic response it is important to verify if the modeled system had the same dynamic response has the real appliance. Thus, after assembling all the separately parts modeled, an all in one system was constructed and a comparison between experimental data acquired directly from the appliance and the modeled system was made. Figure 3.24 shows the data log variables recorded during the experimental tests with the simulations results. The main variables used to validate the model were water inlet temperature, water outlet temperature, setpoint temperature and water flow.

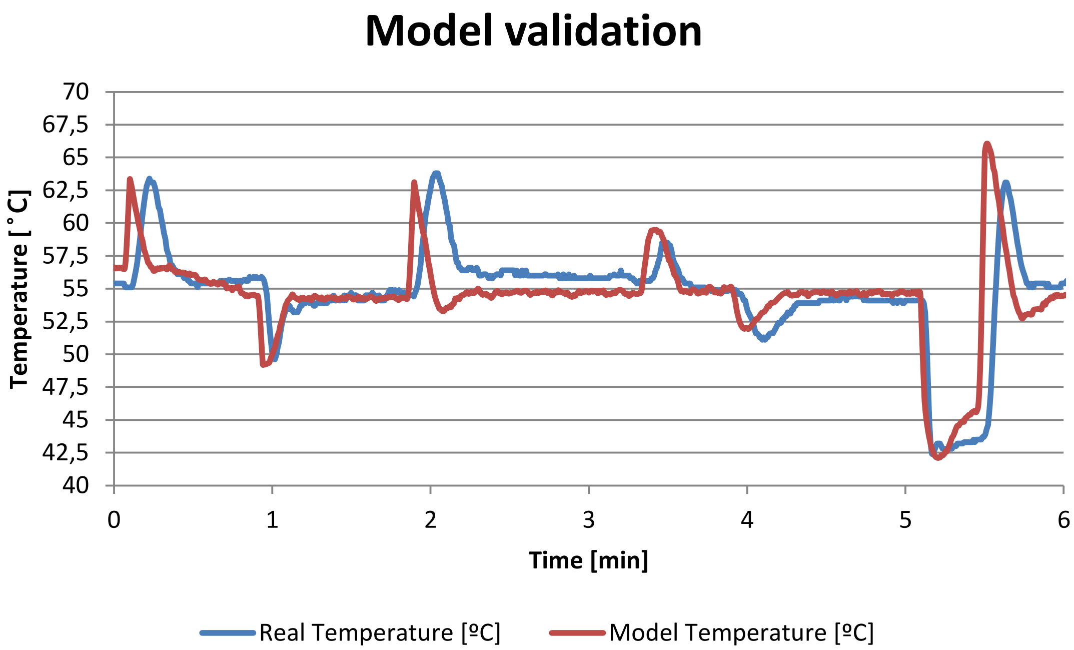

Figure 3.24 - Model validation graphic with real temperature compared to modeled

In the test made, the appliance had specific control architecture with well-defined control values. Because of that, a study of the control code implemented in the appliance was made and then implemented in the simulation model. This way it is guaranteed a more accurate assessment.

From the result of these tests it can be concluded that the simulation model is close to the real appliance. The forward in time is due to the hot water sensor position in the appliance compared to the position on the model. Also, the peak amplitudes have a significant deviation but not enough to compromise the simulated validation. Those deviations from reality came from the simplifications made before in each part of the system.

It is important to underline the real application of this model that is simulate a real appliance to perform a comfort optimization, this way even if the temperature peaks are with different values they represent a real dynamic response that it will be possible to work on.

3.6. Control Architecture

Taking into account the main goal, from experimental data it is possible to understand which dynamic behaviors must be eliminated. Figure 3.25 is a good example of some dynamic behaviors that must be eliminated or if not possible, reduced as much as possible. As it can be seen, the red line represents the output temperature of the appliance with a set point temperature of 55 ºC.

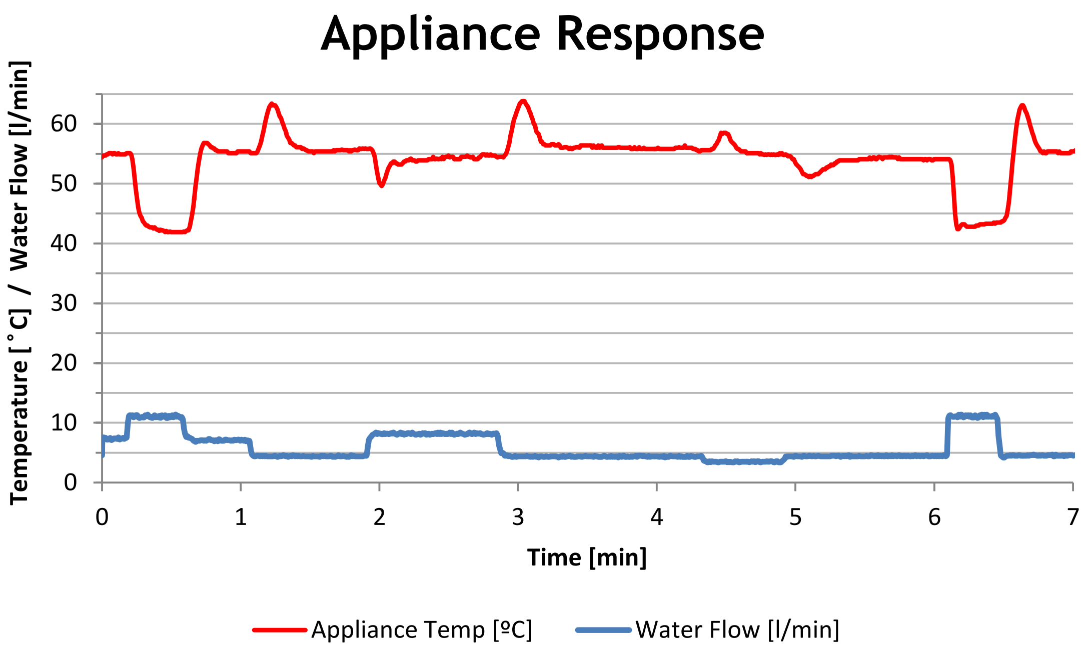

Figure 3.25 - Appliance response temperature

In the instant before 3 min, the water flow change to a lower flow rate, due to dynamic restrictions and the control present in the appliance, the water outlet temperature increases significantly passing above set point temperature, which is very uncomfortable and can harm the user. Also in the instant before 2 min the water flow increases quickly, then again for the same reasons the appliance can't compensate properly this dynamic and a decrease in temperature is obtained. This test was performed near full power of the appliance. The parameters were the defined by [EN13203] for appliance tests.

3.6.1. Gain Scheduling

Studies on PID parameter varying and possible implementations of fuzzy with the PID are made on [9-11]. Those methods are important for a robust and effective control action over the process. On [10] there is concluded that the dynamic behavior of a fuzzy-PID controller using minimum inference engine and center average defuzzification behaves approximately like a parameter varying PID controller, thus a fuzzy gain scheduling controller. The generic diagram for this controller for the simulation environment can be represented as in Fig. 3.26.

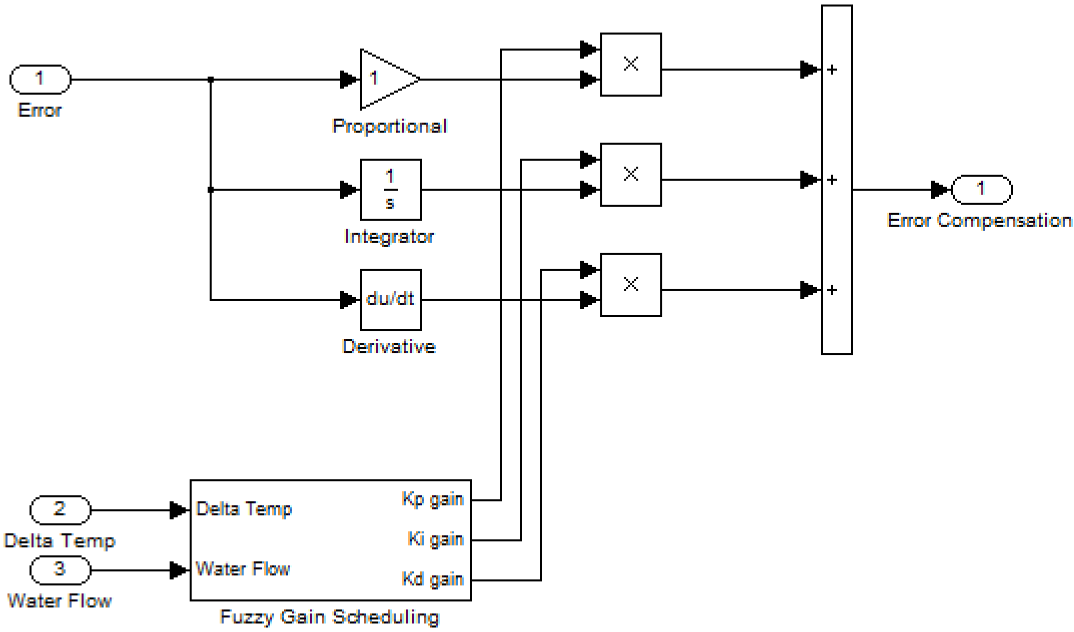

Figure 3.26 - Possible diagram of fuzzy gain scheduler

The implementation of the controller is described next in the implementation chapter.

3.6.2. Bypass

Before introducing the control scheme is important to understand the physics behind the control. As studied before in chapter two, for the water pipe system is considered the mass conservation principle. This consideration is a base principle for all the assumption made further. Let us consider the physical configuration demonstrate in Fig. 3.27.

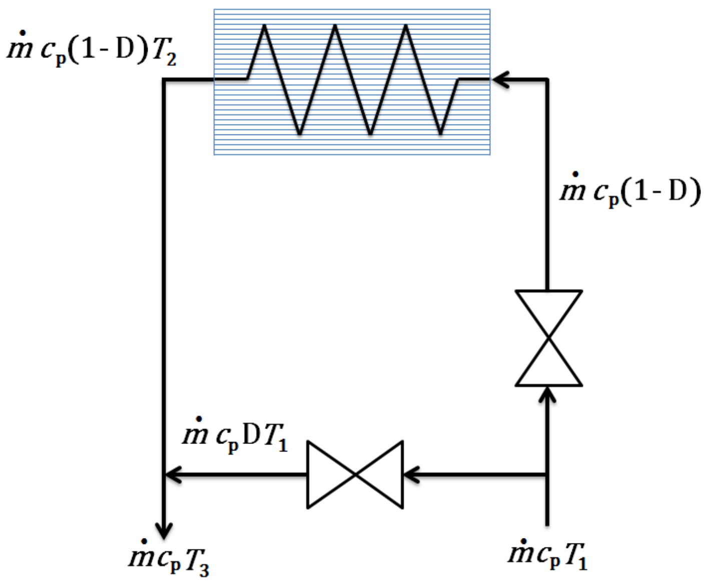

Figure 3.27 - Diagram of bypass configuration for the appliance

Being defined the configuration and variables it is then possible to describe the system into equations.

$$\dot{m}C_pT_3 = \dot{m}DC_pT_1 + \dot{m}(1-D)C_pT_2 \tag{3.22}$$

$$T_3 = DT_1 + (1-D)T_2 \tag{3.23}$$

$$D = \frac{T_3 - T_2}{T_1 + T_2} \tag{3.24}$$

In the point of view of the system variables, T_3 is the setpoint temperature desired, T_2 is the temperature measured in the outlet of the heat exchanger and T_1 is the inlet temperature. With Eq. (3.24) it is possible to calculate the ratio D to control the bypass configuration water valves. Another consideration that must be taken into account is that the range in D must be saturated between zero and one.

3.7. Resume

With all the actuators modeled it is then possible to assemble the parts and construct an overall system. Figure 3.28 demonstrates as the model can be used without a deeper knowledge of the layers inside.

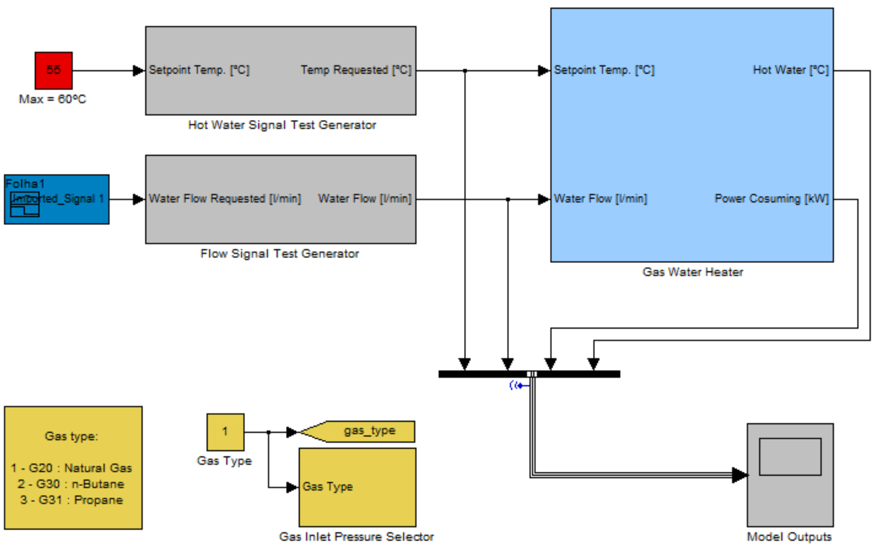

Figure 3.28 - Overall overview of the gas water heater model

The system is also capable of being detached in several parts to make different configurations with the work already done. This provides the ability to upgrade the blocks made without spend too much time on it.

This model also favors the implementation of control schemes. It is easy to see the variables that are being used, this is very intuitive for understand what to control and the range of the variables.

Chapter 4

Implementation and Results

In the previous chapter ideal situations were considered in order to simplify the construction of a solid and not too much complex model. Despite of some simplifications here are discussed some of them and understand its real weight in the dynamic response.

As an appliance for domestic dwellings it must be understood the hot water needs that will be present. This way, there must be considered use cases. After this analysis it will be a more approachable to tune the control structure.

Also a computer controller is implemented. Thus a description of the discretization process and considerations taken in account are presented.

In the end, the results from the simulation control model are compared with the same control in the real appliance.

4.1. Simplifications Issues

As said before, in chapter three, for the simulation model some simplifications were made in order to simplify the system. Although when simulation results were compared to real appliance it was clear that some important aspects might be neglected when they shouldn't. Here we discuss the simplification problem that might be arising from the sensors of water temperature and water flow. It is important to understand these two type of sensors because they are the principal variables of the control.

4.1.1. Temperature Sensor

Water temperature sensors are very important in the control. In specific, the water outlet temperature sensor is the one that will generate the error signal and the water inlet temperature sensor provides one of the variables to compute de amount of heat required to heat the water.

Taking into account the overall time constant of the system, the response delay time of the temperature sensors and its resolution are suitable for the application, otherwise, in the simulation model there would be needed to make specific blocks that would describe the behavior of the temperature sensors.

4.1.2. Water Flow Sensor

Water flow sensor is a key component in the control system, is from it that sudden changes in water flow can be interpreted by the control. If the values read are wrong or have a huge delay, wrong heat computations will be made.

These hypotheses have to be analyzed and understand carefully. Considering the time delay that the sensor senses changes in the flow is very important, this capability can compromise the overall performance of the appliance. If the flow is sensed by the control too late or it is reading wrong values there will be great offsets in temperature that can cause harm to the user and even for the appliance itself.

4.2. Implementation on the Model

Before implementing the control methodologies in real appliance we proceed with the implementation on the modeled system.

4.2.1. Gain Scheduling

Figure 4.1 demonstrates de black box of the gain scheduling implementation. Inside there are specific appliance control schemes. Those are similar to the one mentioned before in chapter three.

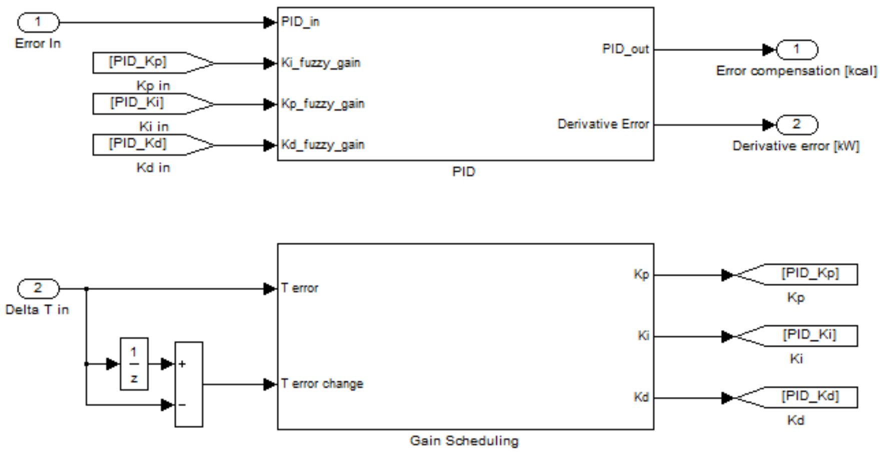

Figure 4.1 – Diagram blocks for the gain scheduling control

4.2.2. Bypass

Mixing water temperatures with different flow ratios is one of the methods presented to overcome temperature overshoots. Due to the possible advantages its implementation was carried out. The principal actuators needed to perform the bypass control are two water valves and a T-junction, Fig. 4.2. Studies on these methodologies were developed on [12] and [13].

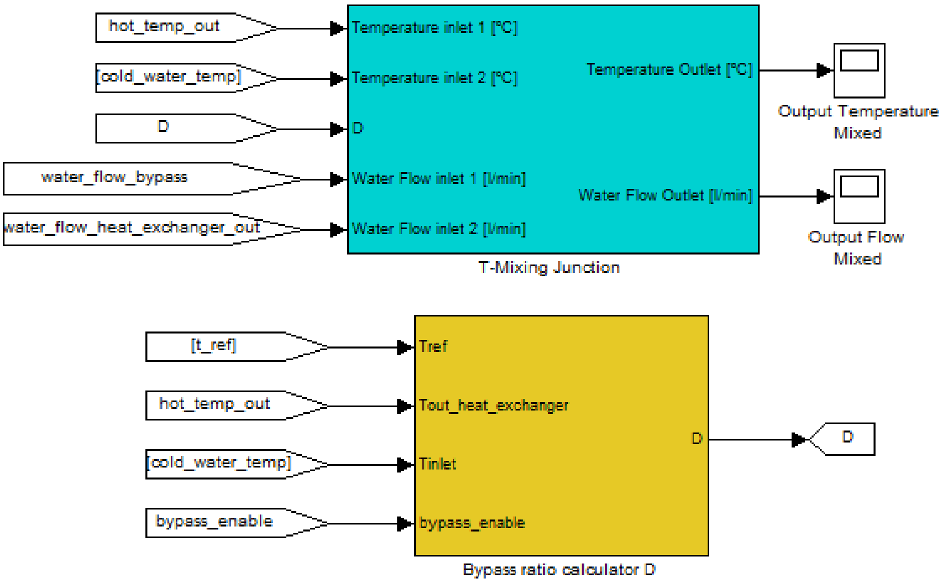

Figure 4.2 - Diagram blocks of the T-junction and Bypass ratio calculator D

Figure 4.3 represents the physical implementation of the bypass control. This is important to understand due possible relevant time delays in the water pipe system. Equation (4.19) gives the general expression of delay for fluids in pipes. Table 4.1 shows that delays.

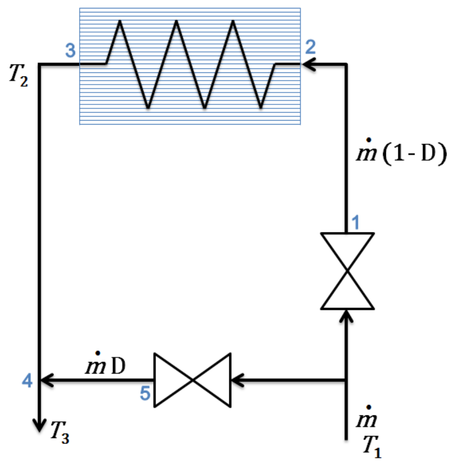

Figure 4.3 - Physic diagram implementation of bypass control

$$t_{delay} = L\frac{A}{\dot{m}} \tag{4.19}$$

Table 4.1 - Water delay time in the appliance pipes

Water pipe length	*Water Flow Delay Time*
$\mathrm{t_{delay}} L_{1 \mapsto 2}$	$\mathrm{t_{delay}} t_{1 \mapsto 2} = \dfrac{L_{1 \mapsto 2} A}{\dot{m}(1-D)}$
$\mathrm{t_{delay}} L_{3 \mapsto 4}$	$\mathrm{t_{delay}} t_{3 \mapsto 4} = \dfrac{L_{3 \mapsto 4} A}{\dot{m}(1-D)}$
$L_{5 \mapsto 4}$	$t_{5 \mapsto 4} = \dfrac{L_{5 \mapsto 4} A}{\dot{m}}$

Results

As can be seen in Fig. 4.4 the bypass control method is efficient for the main goal. There are no overshoots present in the dynamic response in the output of the T-junction due to the turbulent mixing [13] and energy conservation principle [12].

For the implementation of this methodology the time delay present in the system due to water flow in the pipes were neglected. Without this simplification the D factor would need to be adjusted with the times calculated in Table 4.1.

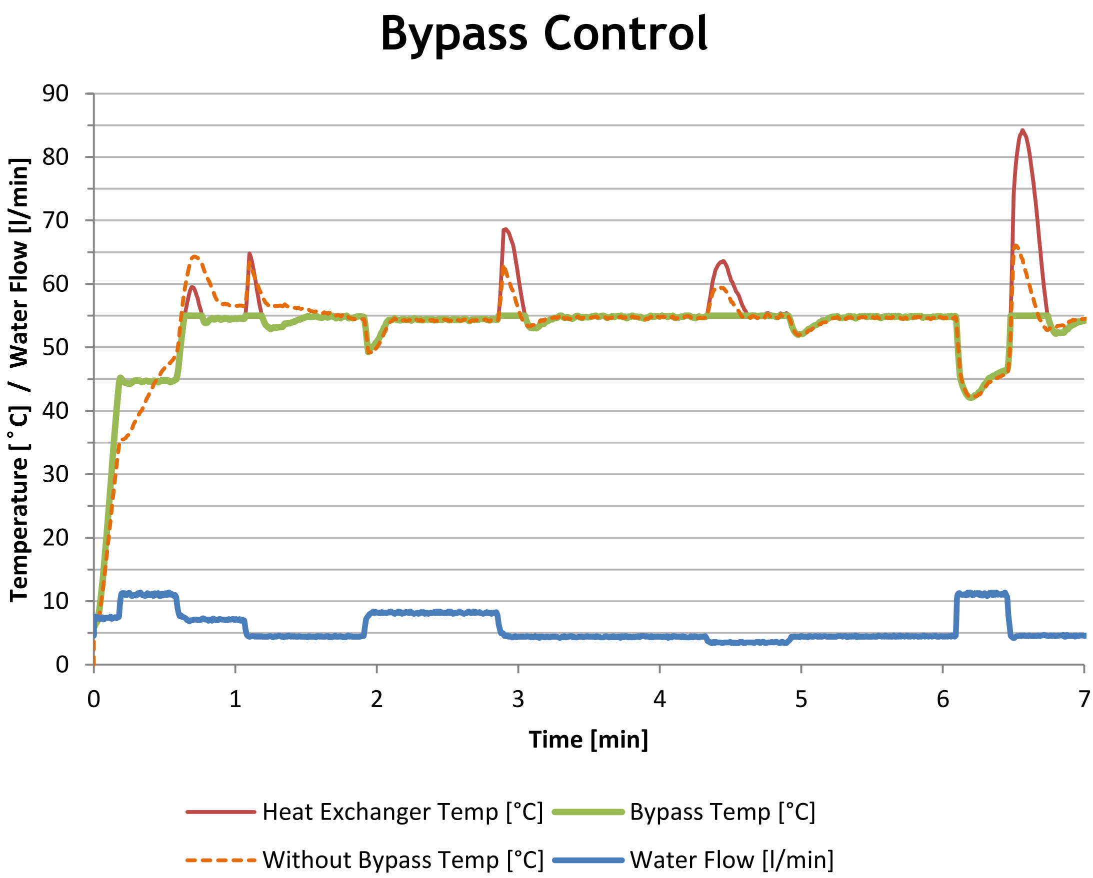

Figure 4.4 - Bypass control response graphic

It is important to evidence what occurs during a fall in water flow. For example in time 6,5 min occurs a high fall in water flow, then the bypass ratio calculator gives the signal to suppress the water flow for the heat exchanger and opens the cold water flow. This situation leads to high temperature in the heat exchanger that can damage the appliance or activate the safe mode then shutting down the gas water heater. It is then important to take into account this behavior.

4.3. Implementation on the Appliance

4.3.1. Discretization

The process of discretization concerns to transform a continuous model to equations into discrete parts. This process is needed in order to implement mathematical equations into digital processors.

Discrete-Time Integrator

The integrator is present in almost all equations present in this system. The time delays are present in the actuators, mass inertias, etc, and those are calculated with time integrators. Also for control they are very important to understand and compute the correct amount of error accumulated. Thus, is quite important to discretize correctly the integrator. Some approaches are possible. Matlab/Simulink provides the follow methods: Forward Euler, Backward Euler and Trapezoidal. The method chosen was the Forward Euler due its simple implementation and low cost computation. If the sample time is smaller than the time constant of a system this method adds small global error. The expression for the discrete-time integrator is then shown below in Eq. (4.4) [2] in which h_s is the sample time, T_i integral time and e the control error.

$$I(t) = \frac{K_I}{T_i}\int_0^t e(s)ds \tag{4.1}$$

$$\frac{dI}{dt} = \frac{K_I}{T_i}e \tag{4.2}$$

$$\frac{I(t_{k+1}) - I(t_k)}{h_s} = \frac{K_I}{T_i}e(t_k) \tag{4.3}$$

$$I(t_{k+1}) = I(t_k) + \frac{K_I h_s}{T_i}e(t_{k+1}) \tag{4.4}$$

In microprocessor code it is possible to define the initial conditions of each integrator used, define the upper and lower limits to prevent windup and to reset the integrator value.

Discrete-Time Differentiator

As the integrator the differentiator is also very important to describe differential equations. For the controller is necessary to compute de error change. Using the Euler backward method as the integrator, the discrete differentiator is described by Eq. (4.7) [2] in which N is the derivative gain limitation, T_d derivative time and D the derivative component. The approximation in Eq. (4.5), instead of $D = sT_dY$, acts as a derivative for low-frequency signal components, avoiding then measurement of noise.

$$D = -\frac{skT_d}{1 + s\frac{T_d}{N}}Y \tag{4.5}$$

$$\frac{T_d}{N}\frac{D(t_k) - D(t_{k-1})}{h_s} + D(t_k) = -K_dT_d\frac{e(t_k) - e(t_{k-1})}{h_s} \tag{4.6}$$

$$D(t_k) = \frac{T_d}{T_d + Nh_s}D(t_{k-1}) - \frac{K_dT_dN}{T_d + Nh_s}(e(t_k) - e(t_{k-1})) \tag{4.7}$$

The advantage by using a backward difference is that the parameter $T_d/(T_d + Nh_s)$ is in a range of 0 to 1 for all values of the parameters guarantee then that the difference equation is always stable.

4.3.2. Gain Scheduling

The control architecture implemented in the ECU is represented by the block of Fig. 4.5. In the “PID” block are implemented in C code the Eq. (4.4) and (4.7). The inputs in “PID” block are connected with the gain scheduling. With different temperature error the gains are changed in order to perform a better dynamic response.

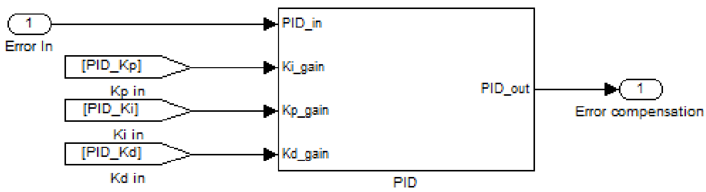

Figure 4.5 - PID implementation block

4.3.3. Results

To perform a comparison between the appliance controller and the new scheduling controller a set of different water flow requests were made all with the same setpoint temperature of 50 ºC. The water flow requests were made by hand with a tap, this way the tests performed aren’t exactly the same but very similar.

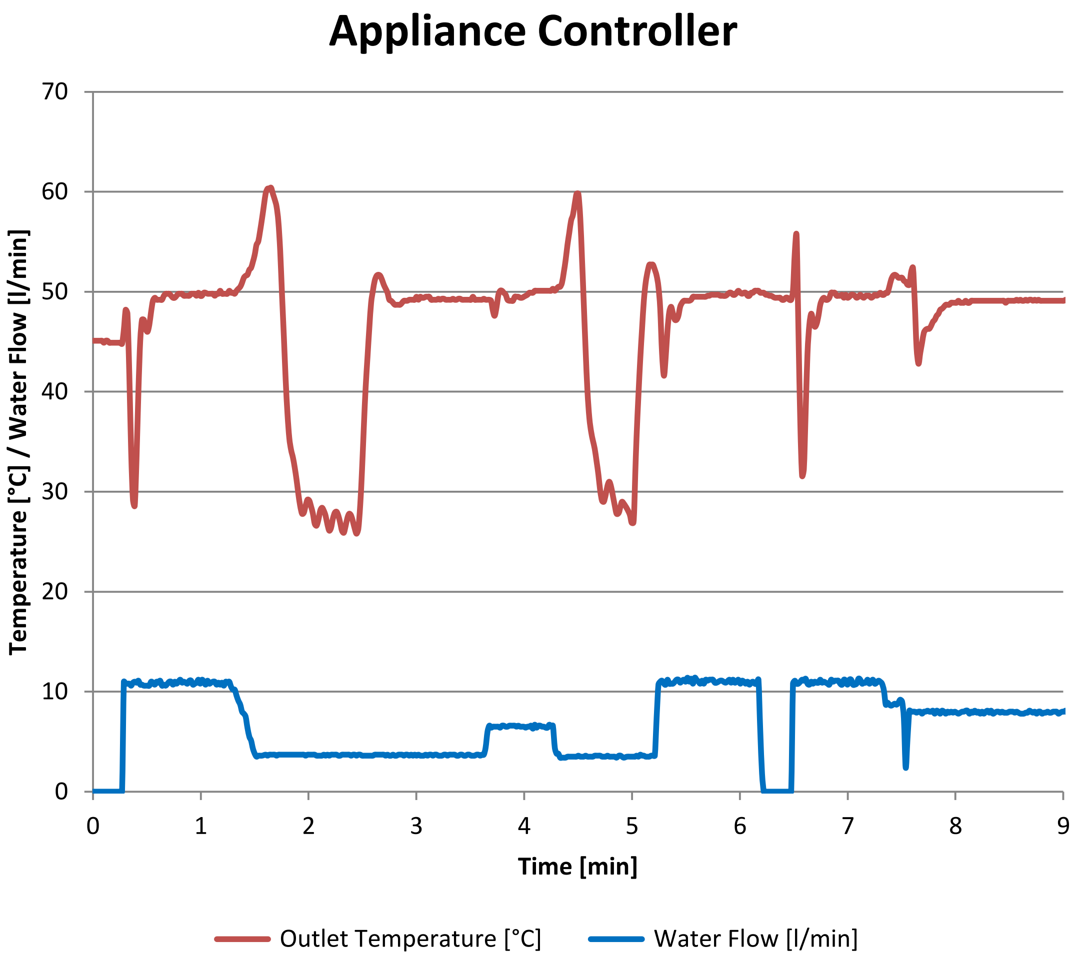

Figure 4.6 - Test performed from the appliance with original controller

From the test made we can see in Fig. 4.6 that near instant 2 min and 3,5 min the appliance might enter in a safe mode due to high increase in the combustion power. Also the setpoint temperature is followed with some offset.

For the new gain schedule controller implemented the same conditions were performed as equal as possible as previously in Fig. 4.6. The setpoint temperature, as it can be seen in Fig. 4.7, is the same as performed in the appliance controller. From Fig. 4.7 we can see that the output temperature follows the setpoint temperature in a more precise way than in the appliance controller.

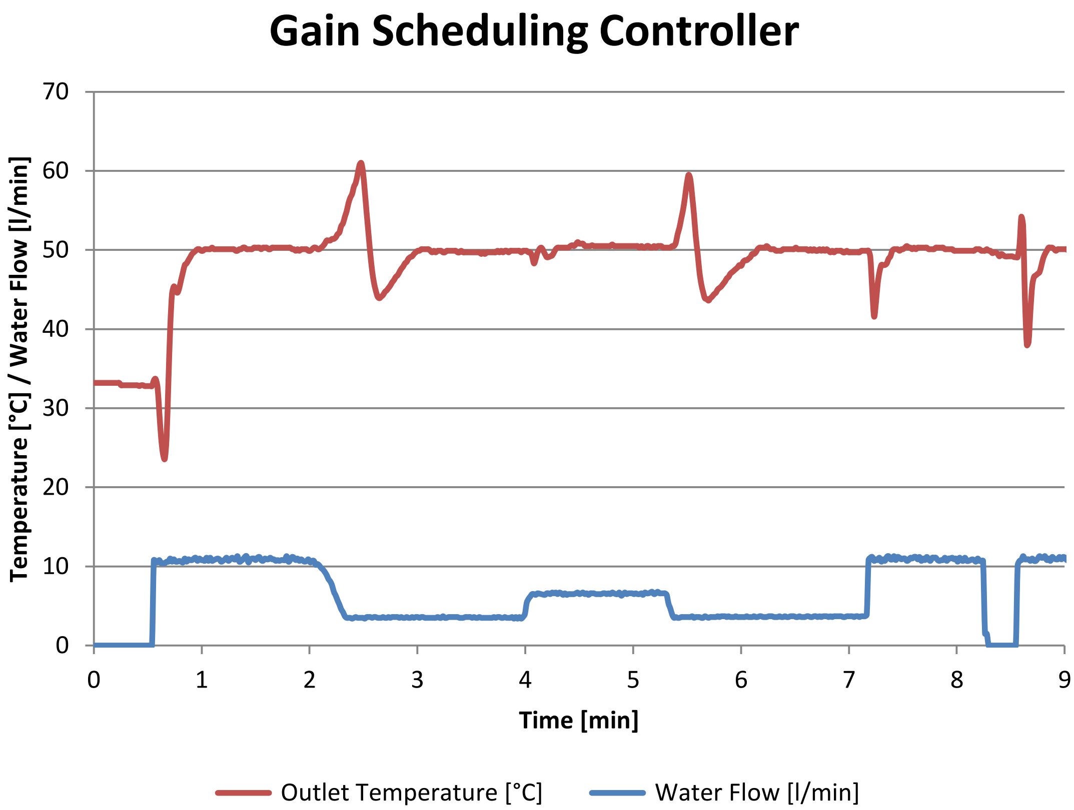

Figure 4.7 - Test performed form the appliance with the gain scheduling controller

In Fig. 4.7 it is observed that steady state error is smaller than in Fig. 4.6, this behavior is due to an increase in the integral action of the controller and decrease in derivative. The derivative action as a term that allows prediction of the future error if is to high will sense the small changes in water flow that can be considered as noise, then, for steady state condition the term must be small.

4.4. Resume

Through these results it can be conclude that the appliance has physical limitations that don't allow a great improvement in dynamic response with its own actuators.

Even though, with the gain scheduling controller it is possible to achieve a better steady state error and thus follow the setpoint temperature more precisely.

With the upgrade of the bypass methodology, using two water valves and a T-junction, by simulation it is possible to achieve a total cancelation of the overshoots.

Chapter 5

Conclusions

In this chapter are presented the conclusions upon the simulations and implementation made and discuss the possibilities to overcome unwanted dynamics from the system.

5.1. Simulation

The ability to represent real systems into a set of equations capable of perform a good representation of reality is a time consuming and difficult task to accomplish. In this work an overall model was implemented with success regarding the main objective of this dissertation.

As the main goal of this work was not to develop an exact model of a gas water heater but instead improve its comfort some aspects in the model were simplified or even neglected.

Those neglected aspects were made on the gas valve, blower, ratio control (λ – control), pipe lengths and sensors position. The most relevant might have been the pressure along the system from inlet air to flue gas exhaust. Despite it has been neglected those aspects, in the overall the model was performing as needed.

5.2. Overshoots

These dynamics were always the most unwanted from all possibilities. From the point of view of comfort it is extreme important to suppress those responses. Here we discuss why those peaks are present and how to eliminate them.

As we studied before, these dynamics appear during quick negative changes in water flow. The question that can be made is 'why they appear?' and this can be answered based on the knowledge gained during the working principle studies.

Water temperature overshoot appears due to slow response of the system components, respectively the air fan and gas valve. As the water flow fall quickly, the combustion process can't be stopped instantaneously to establish the heat necessary for that change. We conclude that the minimum time of overshoot was already implemented previously. To overcome that problem extra actuators must had been implemented is the system.

Bypass Valve

This possibility is the most suitable for the system as shown in the implementation chapter. It provides a good response without compromising the overall performance, in particular the waiting time imposed in the [EN13203-1] that is the factor whit most weight in the total performance calculation. Table 2.6 in chapter 2 shows that importance.

5.3. Undershoots

Undershoots are also a dynamic problem present in the system. Similarly as the overshoots, the undershoots appear when sudden increase in water flow is present and due to the same problem as for overshoots, the system can't respond quickly enough.

In order to prevent this dynamic response an improvement in the actuators delay time or the solution of a water tank working as an inertia accumulator must be taken in account. These two solutions have their problems, the first requires an associated investment and the second compromises the performance quantification of the appliance.

The undershoots affect the comfort as well known but, taking into account that they don't injure the user, unlike the overshoots, thus the undershoots are below in priority than overshoots.

5.4. Future works

As future works several aspects could be done in two different aspects. First in the model point of view, as mentioned above on the simulation conclusions. The second respecting to implementation on the appliance, it would be of great value to implement the bypass controller.

References

[1] H. C. Van Ness, J. M. Smith. “Introduction to Chemical Engineering Thermodynamics”. McGraw-Hill, Fourth edition, 1987.

[2] K. Åström, T. Hägglund. “PID Controllers: Theory, Design, and Tuning”. ISA, second edition, 1995.

[3] D. Bhope, P. Padole, 2004. “Experimental and theoretical analysis of stresses, noise and flow in centrifugal fan impeller”. Mechanism and Machine Theory, 39:1257-1271.

[4] K. Passino, S. Yurkovich. “Fuzzy control”. Addison-Wesley, edition of 1998.

[5] European Standard EN13203-2. “Gas-fired domestic appliances producing hot water – Appliances not exceeding 70 kW heat input and 300 l water storage capacity - Part 1: Assessment of performance of hot water deliveries”. CEN, July 2006.

[6] European Standard EN13203-2. “Gas-fired domestic appliances producing hot water – Appliances not exceeding 70 kW heat input and 300 l water storage capacity - Part 2: Assessment of energy consumption”. CEN, June 2006.

[7] J. Jeng, W. Tseng, M. Chiu, 2013. “A one-step tuning method for PID controllers with robustness specification using plant step-response data”. Chemical Engineering Research and Design, 92:545-558.

[8] R. Champagne, S. Boyle, 1996. “Optimizing valve actuator parameters to enhance control valve performance”. ISA Transactions, 35:217-223.

[9] M. Miccio, B. Cosenza, 2014. “Control of distillation column by type-2 and type-1 fuzzy logic PID controllers”. Journal of Process Control, 24:475-484.

[10] T. Huang, H. Chung, J. Lin, 1999. “A fuzzy PID controller being like parameter varying PID”. IEEE International Fuzzy Systems Conference Proceeding, Seoul, Korea, 1:269-276.

[11] A. El-Nagar, M. El-Bardini, 2014. “Practical implementation for the interval type-2 fuzzy PID controller using a low cost microcontroller”. Ain Shams Engineering Journal, 5:475-487.

[12] R. Stevenson, Z. Yang, V. Jairazbhoy, 2008. “Transient Bernoulli flow in multi-port fluid devices with arbitrary geometry”. Applied Mathematical Modelling, 32:123-140.

[13] M. Gritskevich, A. Garbaruk, T. Frank, F. Menter, 2014. “Investigation of the thermal mixing in a T-junction flow with different SRS approaches”. Nuclear Engineering and Design, only accepted.

Bibliography

M. Rajhi, R. Ben-Mansour, M. Habib, M. Nemitallah, 2014. “Evaluation of gas radiation models in CFD modeling of oxy-combustion”. Energy Conversion and Management, 81:83-97.

T. Kamada, H. Nakamura, T. Tezuka, S. Hasegawa, K. Maruta, 2013. “Study on combustion and ignition characteristics of natural gas components in a micro flow reactor with a controlled temperature profile”. Combustion and Flame, 161:37-48.

Z. Zhang, H. Zhang, T. Wang, M. Jia, 2013. “Effects of tumble combined with EGR (exhaust gas recirculation) on the combustion and emissions in a spark ignition engine at part loads”. Energy, 65:18-24.

H. Zhen, Y. Choy, C. Leung, C. Cheung, 2011. “Effects of nozzle length on flame and emission behaviors of a multi-fuel-jet inverse diffusion flame burner”. Applied Energy, 88:2917-2924.

A. Sobiesiak, J. Wenzell, 2005. “Characteristics and structure of inverse flames of natural gas”. Proceedings of the Combustion Institute, 30:743-749.

L. Jia, X. Peng, Y. Yan, J. Sun, X. Li, 2001. “Effects of water vapor condensation on the convection heat transfer of wet flue gas in a vertical tube”. International Journal of Heat and Mass Transfer, 44:4257-4265.

R. Rihani, A. Bensmaili, J. Legrand, 2009. “Fuzzy logic modelling tracer response in milli torus reactor under aerated and non-aerated conditions”. Chemical Engineering Journal, 152:566-574.

J. Mendes, R. Araújo, F. Souza, 2013. “Adaptive fuzzy identification and predictive control for industrial processes”. Expert Systems with Applications, 40:6964-6975.

Z. Li, Z. Qin, Z. Wu, S. Li, Y. Zhang, M. Dong, W. Fan, J. Wang, 2014. “Fuzzy logic control of a reverse flow reactor for catalytic oxidation of ventilation air methane”. Control Engineering Practice, 25:112-122.

G. Liu, M. Liu, 2011. “Development of simplified in-situ fan curve measurement method using the manufacturers fan curve”. Building and Environment, 48:77-83.

C. Long, J. Guan, 2011. “A method for determining valve coefficient and resistance coefficient for predicting gas flowrate”. Experimental Thermal and Fluid Science, 35:1162-1168.

A. Heinsbroek, 1997. “Fluid-structure interaction in a non-rigid pipeline systems”. Nuclear Engineering and Design, 172:123-135.

S. Baek, J. Nam, H. Hong, C. Kim, 2011. “Effect of brine flow rate on the performance of a spiral-jacketed thermal storage tank used for SDHW systems: A computational fluid dynamics study”. Applied Thermal Engineering, 31:2716-2725.

O. Ibrahim, F. Fardoun, R. Younes, H. Louahlia-Gualous, 2013. “Review of water-heating systems: General selection approach based on energy and environmental aspects”. Building and Environment, 72:259-286.

A. Arce, N. Dowell, N. Shah, L. Vega, 2012. “Flexible operation of solvent regeneration systems for CO2 capture processes using advanced control techniques: Towards operational cost minimization”. International Journal of Greenhouse Gas Control, 11:236-250.

P. Balaguer, V. Alfaro, O. Arrieta, 2010. “Second order inverse response process identification from transient step response”. ISA Transactions, 50:231-238.

F. Incropera, D. DeWitt. “Fundamentals of Heat and Mass Transfer”. John Wiley & Sons, Fifth edition, 2002.

K. Åström, B. Wittenmark. “Computer-Controlled Systems: Theory and Design”. Prentice Hall Information and System Sciences Series, Third edition, 1997.